THE EVOLUTION OF CLIMATE

THE EVOLUTION OF CLIMATE

BY

C. E. P. BROOKS,

M.Sc., F.R.A.I., F.R.Met.Soc.

WITH A PREFACE BY

G. C. SIMPSON, D.Sc., F.R.S.,

DIRECTOR OF THE METEOROLOGICAL OFFICE
(LONDON)

R. V. COLEMAN

NATIONAL BOOK BUYERS' SERVICE

522 FIFTH AVENUE, NEW YORK

First Published - - - *November*, 1922
Second Edition - - - *January*, 1925

MADE AND PRINTED IN GREAT BRITAIN

PREFACE

Geologists very early in the history of their science, in fact as soon as fossils began to be examined, found indisputable evidence of great variations in climate. The vegetation which resulted in the coal measures could have grown only in a sub-tropical climate, while over these are vast remains of ice-worn boulders and scratched rocks which obviously have been left by ice existing under polar conditions. Such records were not found only in one region, but cropped up in juxtaposition in many parts of the world. Remains of sub-tropical vegetation were found in Spitzbergen, and remains of an extensive ice-sheet moving at sea-level from the south were clearly recognized in central and northern India. At first it was simply noticed that the older fossils generally indicated a warmer climate, and it was considered that the early climate of a globe cooling from the molten state would be warm and moist, and so account for the observed conditions. It was recognized that the ice remains were relatively recent, and so far as a cause for the Ice Age was sought it was considered that astronomical changes would be sufficient.

It was only when geologists began to find records of ice ages far anterior to the Carboniferous Age, and astronomers proved by incontrovertible observations and calculations that changes in the earth's orbit, or its inclination to that orbit, could not account for the ice ages, that the importance and inexplicability of the geological evidence for changes of climate came to be clearly recognized.

During the last few years much study has been given to "palæoclimatology," but such a study is extremely difficult. Only a very small fraction of the total surface of the earth can be geologically examined, and of that fraction a still smaller proportion has up to the present been studied in detail. There has been a great tendency to study intently a small region and then to generalize. The method of study which has to be employed is extremely dangerous. A geological horizon is determined by the fossils it contains. Wherever fossils of a certain type are found the strata are given the same label. Isolated patches correlated by their fossils are found in different parts of the world, and it is frequently assumed not only that these rocks were laid down at the same time, but that the conditions which they indicate existed over the whole of the earth's surface simultaneously. Thus geologists tell us that the climate of the Carboniferous Age was warm and damp; of the Devonian Age cool and dry; of the Eocene Age very warm; of the Ice Age very cold.

But has the geologist given sufficient attention to the climatic zones during the various geological climates? It is true that the geologist has definitely expressed the view that in certain ages climatic zones did not exist; but from a meteorological point of view it is difficult to see how the climate could have been even approximately the same in all parts of the world if solar radiation determined in the past as in the present the temperature of the surface of the earth.

The climatic zones of the various geological periods will need much closer study in the future; the data hardly exist at present, and the great area covered by the ocean will always make the study difficult and the conclusions doubtful. Admitting, for the sake of argument only, large changes in average conditions, but with zonal variations of the same order of magnitude as those existing to-day, the slow changes from period to period will cause any given climatic state to travel slowly over

the surface of the earth, and this will so complicate the problem as to make it doubtful whether any conclusions can be reached so long as the same criteria are used to determine both the geological epoch and the climatic conditions.

These considerations apply more particularly to the earlier records, while Mr. Brooks has confined his work chiefly to the later records, beginning with those of the Great Ice Age, in which climatic zones are clearly indicated by the limits of the ice; but in this problem one cannot confine one's attention to a portion of the record, for the test of any explanation must be its sufficiency to explain all the past changes of climate. One will not be satisfied with an explanation of the Great Ice Age which does not explain at the same time the records of earlier ice ages, of which there is indubitable evidence in the Permo-Carboniferous and Pre-Cambrian periods, and the records of widespread tropical or sub-tropical conditions in the Carboniferous and Eocene Ages. Whether Mr. Brooks' theory for the cause of the recent changes of climate satisfies this criterion must be left to each reader to decide.

As Mr. Brooks says, the literature on this subject is now immense, and it is most unsatisfactory literature to digest and summarize. In the first place, many of the original observations which can be used in the study of past climates are hidden away in masses of purely geological descriptions, and a great deal of mining has to be done to extract the climatic ore. Then, again, most of the writers who have made a special study of climatic changes have had their own theoretical ideas and most of their evidence has been *ex parte*. To take a single example, for one paper discussing dispassionately the evidence for changes in climate during the historical period, there have been ten to prove either that the climate has steadily improved, steadily deteriorated, changed in cycles or remained unchanged. It is extremely difficult to arrive at the truth from such material,

and still more difficult to summarize the present state of opinion on the subject.

It may be complained that Mr. Brooks has himself adopted this same method and has written his book around his own theory. But was there any alternative? There are so many theories and radically different points of view that no writer could confine himself to the observations and say what these indicate, for the indications are so very different according to each theory in turn. And new theories are always being propounded; since Mr. Brooks commenced to write this book, Wegener has put forward his revolutionary theory according to which the polar axis has no stability, and the continents are travelling over the face of the globe like debris on a flood. Where is there solid ground from which to discuss climatic changes if the continents themselves can travel from the equator to the pole and back again in the short period of one or two geological epochs?

Mr. Brooks has studied deeply geology, anthropology, and meteorology, and he has considerable mathematical ability. By applying the latter to the results of his studies he has developed a theory for the cause of climatic changes based on changes of land and sea area, and on changes of elevation of land surfaces, and naturally he has made this theory the basis of his work.

That there will be some who are not able to agree with him as to the sufficiency of the causes he invokes, or who may even question whether he also has not taken for granted what others dispute, goes without saying; but all will agree that he has presented a difficult subject in a clear and concise way, and that meteorologists (and may I add geologists?) owe to him a deep debt of gratitude.

G. C. Simpson

CONTENTS

INTRODUCTION TO THE SECOND EDITION

On the whole, the first edition of "The Evolution of Climate" met with a good reception. The meteorological interpretation of the succession of climatic stages during the Quaternary Ice Age and subsequently was especially welcomed, and it appears that with the spread of our knowledge of the climatic conditions of different parts of the world during the various geological periods there will be increasing scope for work of this kind. An important beginning has already been made by F. Kerner-Marilaun (see later). The climatic sequence should be a valuable guide to the complicated stratigraphy of the Quaternary, and mainly on climatic grounds it appeared to me most probable that the Chellean industry, with its warm fauna, occupied the Mindel-Riss interglacial. This conclusion was severely criticized by several British archæologists, on the ground that work in France, especially by H. Obermaier, showed that the Chellean industry probably fell in the Riss-Wurm interglacial. The age of the Chellean is likely to remain controversial for some time, but it may be noted that the French archæologist L. Mayet (1)[1] places the Chellean in the Mindel-Riss interglacial and at the beginning of the Riss glaciation. A similar view is now adopted by H. F. Osborn and C. A. Reeds (2) in a valuable synthesis of the standards of Pleistocene classification; this is a reversal of the view which they expressed in 1914. On the other hand, J. Reid Moir (3) on the basis of his researches in East Anglia, and L. Palmer (4) from work in south-east England, place the

[1] These numbers refer to the Bibliography on page 12.

Chellean in the Gunz-Mindel interglacial. There are thus three views to choose from, and future researches alone can show which is correct. The question is of climatic importance, because the greater part of the Chellean is admitted to have been warm.

With regard to the climatic effect of volcanic dust, Dr. W. J. Humphreys informs me that his suggestion was that volcanic dust may act in conjunction with mountain building and increased elevation of the continents to produce glaciation. On page 18 the figure for the maximum eccentricity should of course have been 0.07775. H. Gams and R. Nordhagen have made a number of helpful criticisms and suggestions. Most of these are referred to in the summary of their recent book (17); they will be introduced into the main text when opportunity offers.

The past two or three years have seen great activity in the study of past climates, and only a few of these researches can be alluded to here. Ellsworth Huntington and S. S. Visher (5) have published a new hypothesis of the main cause of climatic variations. According to their view the climate of the earth is largely governed by changes in solar activity, acting on the position and intensity of the storm belts. An increase in solar activity, represented by an increase in the relative sunspot numbers, is considered to result in an increase of storminess, together with some displacement of the storm tracks. When such a period of increased solar activity occurs with extensive and high continents, and perhaps with other favourable conditions, such as a paucity of CO_2, a glaciation results. This is considered to account for the Quaternary glaciation and probably also for that of the Permo-Carboniferous period, in which the storm tracks lay very far south, and higher latitudes remained unglaciated because they were occupied by deserts. Periods of slight solar activity and few sunspots had slight storminess and steady winds from the equator towards the poles, hence

they were periods of mild and equable climate over the whole earth. The variations of solar activity are connected with changes in the distance of the nearest fixed stars. The theory is attractive, but it presents several very great difficulties. In particular the relationship, if any, between sunspots and storminess at the present day is still very obscure, and does not provide an adequate basis for the enormous superstructure. In this country at least it has not been well received.

A valuable summary of the palæoclimatological evidence from the Antarctic has been presented by C. S. Wright and R. E. Priestley (6). According to this summary, the pre-Cambrian climate of Antarctica was mainly warm temperate, with, however, indications of frost action. In the Cambrian warm temperate to tropical conditions prevailed ; in the Devonian possibly temperate. In the Permo-Carboniferous period, during the glaciation of the tropics, it appears that the high land of Antarctica was an arid windswept desert, but in sheltered lowlands a rich *Glossopteris* flora flourished. There was a considerable seasonal range, but there is no definite trace of glacial conditions. In the Jurassic a sub-tropical to warm temperate climate prevailed, growing cooler through the Cretaceous, until in the Eocene moraine-like deposits doubtfully suggest the first Antarctic glaciation. In the Oligocene sub-tropical to temperate conditions reappeared, followed by the first undoubted glacial evidence. The Miocene may have been a temperate interglacial period, but in the Pliocene glacial conditions again appeared, and persisted until the present, though with diminishing intensity in recent times. This evidence must be taken into account in future discussions of the causes of climatic change.

F. Kerner-Marilaun (7) has studied the influence of Permo-Carboniferous geography on the temperature distribution, assuming a supply of solar energy similar to that of to-day and the present position of the poles.

He finds that under these conditions a high coastal range of hills or plateau in northern India would probably be glaciated. His assumptions include a cold Arctic ocean, and it is doubtful if this is valid, but the paper is a useful indication of the extent to which geographical changes might modify the present more or less zonal distribution of climates. The climatic conditions of Permo-Carboniferous time are peculiar and now appear to be well defined. There was a large expanse of ocean in the northern hemisphere, with several large islands or small continents, in the coastal regions of which the climate of the Coal Measures prevailed, moist and probably rather warm. Isolated mountain areas in the northern hemisphere, however, bore glaciers. In the southern hemisphere, in which the equatorial continent extended much farther south, the hardier *Glossopteris* flora developed in high latitudes, and the climate was probably equable but cool. Thus there was a considerable temperature difference between the two hemispheres, and this would lead to winds crossing the equatorial continent from south to north, similar to the south-west monsoon of India. These winds would deposit great quantities of moisture on the hills, which at altitudes of about ten thousand feet would fall as snow, originating the great ice-sheets of this period. An investigation along these lines appears to present the only possibility of accounting for the inversion of zones in the Permo-Carboniferous period, apart from displacements of the poles or continental drift.

The theory of mild polar climates has also been investigated by F. Kerner-Marilaun (8). He found that the land and sea distribution prevailing in the Upper Jurassic and Middle Eocene periods would lead to winter temperatures in the Arctic many degrees above the present ones. He also found that the cooling effect of the floating ice in the Arctic Ocean is so great that if it could be cleared away the temperature over an open ocean near the pole in January would be only a few

degrees below freezing point. For some reason he did not put these two results together, and apparently he failed to realize that his researches showed that during the two periods chosen the Arctic Ocean must have been free of ice. A recalculation of his figures on this basis (9) gave for the Upper Jurassic a January temperature in 75° N., approximately equal to that now found in the Scilly Isles, while in the Middle Eocene it was only a few degrees lower. The probable winter temperatures calculated on climatological grounds thus fall into very good agreement with those required by palæobotanists from the evidence of fossil floras.

The views of M. Depéret on the correlation of the various Quaternary stages by means of changes of level have attracted a great deal of attention. According to Depéret the various changes of level which he traced in the Mediterranean during the Quaternary were due mainly to movements of the sea and only locally to movements of the land, and he traces the Mediterranean raised beaches round the Atlantic coast to the Baltic and also up the river valleys to the glaciated regions, where they pass into glacial moraines. I accepted Depéret's system as applied to the Mediterranean, but did not take seriously his extension of it to the glaciated regions. Osborn and Reed (2), after a careful examination, also find difficulty in accepting Depéret's correlation of the northern drifts. On the other hand, it has been widely accepted in Europe as a great advance. An objection to the scheme is that each stage except the last includes both a glacial and an interglacial phase; thus the Sicilian includes the Gunzian or Scanian glaciation and the Gunz-Mindel interglacial, the Milazzian includes the Mindelian and the Mindel-Riss, the Tyrrhenian includes the Rissian and the Riss-Wurm, and the Monastirian includes the Wurmian.

A. R. Dwerryhouse (10) has reinvestigated the glaciation of north-eastern Ireland. He finds that this area

was covered first by Scottish ice from the Firth of Clyde, and later by Irish ice from the hills of Donegal. The two glaciations form part of a single maximum, and the ice-sheets from the two centres were probably in contact during part of the retreat of the Scottish ice. The earlier work of Kilroe is mainly confirmed, with some corrections of detail.

The late-glacial and post-glacial history of the Baltic continues to be actively studied, and a number of papers on the subject have appeared in the past two years. E. Antevs (11) has contended that the *Ancylus* elevation in the south-west Baltic region has been over-estimated. He considers that during *Ancylus* time the Baltic was never a true lake, but was an inland sea connected with the Atlantic by a narrow channel, and kept fresh by the enormous volume of water supplied by the melting Scandinavian ice-sheet. This view is accepted by G. de Geer, but is denied by H. Munthe. It is admitted that the water was fresh, and if there was free communication with the Atlantic it seems improbable that the amount of thaw water during the cold dry winter would be sufficient to keep out the sea water. From the climatological point of view, however, the important point is that the inflow of sea water at a higher temperature was interrupted, and it does not seem to matter greatly which view is correct.

I. Hogbom (12) has reinvestigated "fossil dunes" of northern Europe, and concludes that they were formed by dry winds from west-north-west during Finiglacial time (*ca.* 7000–6000 B.C.) and not to periglacial easterly winds, as formerly supposed. The type of pressure distribution reconstructed from the dunes and other evidence resembles that prevailing during the cold spell of spring.

G. de Geer (13) has been investigating the annual clay-varves of the late-glacial period in North America. It will be remembered that by an examination of similar annual layers in Sweden he arrived at an absolute

measure of the age of various stages of the retreat. He considers that the succession of different thicknesses in certain groups of annual layers in North America bears so close a resemblance to parts of the Swedish succession that they must refer to the same groups of years, and on these grounds he has dated parts of the final stages of the glacial period in North America. The ice left the eastern end of Lake Champlain about 1,100 years before the end of the Ice Age in Sweden (*ca.* 5000 B.C.). In Timiskaming (northern Ontario) the recession was traced for over 600 years, the ice leaving the district 297 years after the close of the Ice Age in Sweden. This indicates that the melting of the inland ice lasted somewhat longer in Canada than in Sweden; but de Geer considers that there can be no more doubt as to the exact agreement between the climatic conditions in the two regions. It is greatly to be hoped that de Geer will publish a table showing the relative thicknesses of each of his annual layers, similar to that published by A. E. Douglass of the width of annual tree-rings. Sir T. W. Edgeworth David (14) has discovered similar banded clays associated with the pre-Cambrian and Carboniferous tillites of Australia, indicating a duration of 12,000 years in the former case and about 4,000 years in the latter.

The fourfold division of the Quaternary Ice Age adopted by Penck and Bruckner for the Alps is gradually being extended beyond the limits of Europe. Sir T. W. Edgeworth David (15) accepts it for the glaciation of Australia and Tasmania; he states that Tasmanian man is now considered to date back probably to the Rissian. The Australian type came later, but the Talgai skull from near Warwick, Queensland, which is placed in the Riss-Wurm interglacial, has Australian affinities. As a result of Dainelli's researches in the Himalayan region, F. Loewe (16) has delineated a fourfold glaciation of the western Himalayas. The second ice-extension was the greatest, the positions of the

snow-line being: Glaciation I, unknown; II, 11,500 feet; III, 12,300 feet; IV, 12,550 feet. The fourth glaciation was followed by retreat stadia as in the Alps. No fossiliferous interglacial deposits are known, so that the correlation with the Alpine stages is problematical.

Finally, I have to mention an important publication by H. Gams and R. Nordhagen (17), dealing primarily with the post-glacial climatic changes in central Europe, but summarizing also the results of recent researches in other parts of the Continent. Their summary commences with the "Great Interglacial" (following the Mindelian glaciation), in which they place the Chellean industry. After this they intercalate a new glacial stage, the Mühlbergian, followed by the short Rabutz interglacial, in which they place the Acheulian. This additional glaciation certainly clears up some difficulties, and facilitates correlation with the (possibly) five-fold American series (H. F. Osborn and C. A. Reeds ignore the Iowan and so make the American series four-fold); but much field-work will be required before geologists will consent to such a modification of Penck and Bruckner's classic scheme. Gams and Nordhagen consider the Rissian glaciation to have been the greatest, instead of the Mindelian; it was followed by the Rixdorf interglacial, also short. The Würm glaciation is divided into a number of stages—Schaffhauser Advance, Laufen Oscillation, Mecklenburgian End Moraine, Alleröd Oscillation, Fennoscandian End Moraine, followed by the other familiar retreat stages. For the post-glacial period the pioneer work of Axel Blytt is regarded as thoroughly confirmed, and his terminology is accepted. The temperature is considered to have risen steadily through the dry Boreal Period (Continental Phase, Azilian-Tardenoisian), the moist Atlantic Period (Maritime Phase), and the dry sub-boreal Period (Later Forest Phase), reaching a maximum 4° F. above the present near 1000 B.C. It was at this period that the hazel reached its greatest extension in northern Scan-

dinavia, and not during the boreal period, as formerly believed. About B.C. 850 occurred a sudden deterioration of climate, which in the Alps had almost the appearance of a catastrophe. This begins the sub-Atlantic Period (Later Peat-bog Phase) which in the opinion of the authors corresponds with the Daun readvance of the Alpine glaciers; after this the climate of Europe passed by a series of oscillations to its present level.

If the results of all the remaining papers published in the past two or three years were discussed, this preface would grow to the size of another book. In the face of such an outpouring of material one's views require constant adjustment, and the most urgent need at the moment, as pointed out by Osborn and Reeds (2), is a stable framework of classification for the Quaternary period, which shall embody at once the glacial advances and retreats, the river terraces and raised beaches, the succession of faunas, both land and marine, and of floras, the human industries and the waves of climate. Unfortunately we seem now to be farther than ever from such a framework. Let us hope that this is the darkest hour which precedes the dawn, and that some generally accepted framework will soon emerge.

C. C. P. B.

January, 1925.

BIBLIOGRAPHY

(1) Mayet, Lucien. "Corrélations géologiques et archéologiques des temps quaternaires." Paris, *C.-R, Ass. franç. avanc. sci.*, 44 Session, Strasbourg, 1920, pp. 481–490.

(2) Osborn, Henry Fairfield, and Chester A. Reeds. "Old and new standards of Pleistocene division in relation to the prehistory of man in Europe." *Bull. Geol. Soc. America*, 33, 1922, pp. 411–490.

(3) Moir, J. Reid. "The Ice-age and Man." *Man*, 1922, p. [52].
———. "The antiquity of man in East Anglia." *Science Progress*, July, 1924, p. 129. See also *The Times*, August 22, 1924.

(4) Palmer, L. S. "The Ice-age and man in Hampshire." *Man*, 1922, p. 106.

———, and J. H. Cooke. "The Pleistocene deposits of the Portsmouth district and their relation to man." London, *Proc. Geol. Ass.*, 34, 1923, p. 253.

(5) Huntington, Ellsworth, and S. S. Visher. "Climatic changes, their nature and cause." New Haven, 1922.

(6) British (Terra Nova) Antarctic Expedition 1910–1913. "Glaciology," by C. S. Wright and R. E. Priestley. London (Harrison & Sons), 1922.

(7) Kerner-Marilaun, F. "Untersuchungen über die morphogene Klimakomponente der permischen Eiszeit Indiens." Wien, *Sitzungsber. Akad. Wiss., Math.-nat. Kl.*, Abt. 1, 126 Bd., 1917, pp. 177–228.

(8) ———. "Das akryogene Seeklima und seine Bedeutung für die geologischen Probleme des Arktis." Wien, *Sitzungsber. Akad. Wiss.*, 131, 1922, p. 153.

(9) Brooks, C. E. P. "The problem of mild polar climates." London, *Q. J. R. Meteor. Soc.*, 51, 1925.

(10) Dwerryhouse, A. R. "The glaciation of north-eastern Ireland." *London Q. J. G. S.*, 79, 1923, p. 352.

(11) Antevs, Ernst. "On the late-glacial and post-glacial history of the Baltic." New York, N. Y., *Geogr. Rev.*, 12, 1922, pp. 602–612.

(12) Hogbom, I. "Ancient inland dunes of northern and middle Europe." Stockholm, *Geogr. Ann.*, 5, 1923, pp. 113–243.

(13) Geer, G. de. "Correlation of late-glacial annual clay-varves in North America with the Swedish time scale." Stockholm, *Geol. Fören. Forh.*, 43, 1921, p. 70.

(14) David, Sir T. W. Edgeworth. "The 'Varve Shales' of Australia." *Amer. J. Sci.* (5), 3, 1922, p. 115.

(15) ———. "Geological evidence of the antiquity of man in the Commonwealth, with especial reference to the Tasmanian aborigines." Hobart, *Papers and Proc. R. Soc. Tasmania*, 1923, pp. 109–150.

(16) Loewe, F. "Die Eiszeit in Kaschmir, Baltistan and Ladakh." Berlin, *Zs. Ges. Erdk.*, 1924, p. 42.

(17) Gams, H., and R. Nordhagen. "Postglaziale Klimaänderungen und Erdkrustenbewegungen in Mitteleuropa." München, *Geogr. Gesellsch., Landesk. Forschungen*, H.25, 1923.

THE EVOLUTION OF CLIMATE

CHAPTER I

FACTORS OF CLIMATE AND THE CAUSES OF CLIMATIC FLUCTUATIONS

The climate of any point on the earth's surface depends on a complex of factors, some of them due to influences arriving from outside the earth, and others purely terrestrial. Since any variations of climate must be due to a change in one or more of these, it is necessary, before we can discuss changes of climate, to consider briefly what the factors are.

The only important extra-terrestrial factor of climate is the amount of radiant energy which reaches the borders of the earth's atmosphere from the heavenly bodies—that is, from the sun, for the moon and stars can be ignored in this connexion. The only other conceivable factor is the arrival of meteorites, bringing kinetic energy, which is converted into heat, and introducing cosmic dust into the atmosphere; but it is highly improbable that this is of appreciable effect.

The amount of solar radiation[1] which reaches the earth depends in the first place on the total radiation emitted by the sun, and in the second place on the distance of the earth from the sun, both of which quantities are variable. It has been calculated that if other factors remained unchanged an increase of ten per cent. in the solar radiation would raise the mean temperature of the earth's surface by about 7° C., or between 12°

[1] By this term we shall in future understand only that part of it which is responsible for thermal effects.

and 13° F., with, of course, a corresponding fall for a decrease.

After the sun's radiation reaches the outer limits of the earth's atmosphere its nature and intensity are modified by the composition of the air through which it passes. In general the air itself is very transparent to the small wave-lengths which make up the solar rays, but the presence of fine dust, whether of volcanic or of cosmic origin, has been shown by Humphreys to be a distinct hindrance to their passage, so that volcanic eruptions of an explosive nature, such as that of Krakatoa in 1883, La Soufriére (St. Vincent) in 1902, or Katmai (Alaska) in 1912, may result in a fall of temperature over the world as a whole.

The temperature of the earth is determined by the balance between the radiation received from the sun and the terrestrial radiation to space, and a decrease in the latter would be as effective in raising the mean temperature as an increase in the former. The use of glass for greenhouses depends on this principle; for glass is transparent to heat rays of small wave-length, but is largely opaque to the rays of greater wave-length which make up terrestrial radiation. Certain constituents of the atmosphere, especially water-vapour, carbon dioxide and ozone, are effective in this way, and variations in the amount of these gases present may affect the temperature.

The angle at which the sun's rays strike the earth's surface is a highly important factor. Within the Tropics the sun at midday is nearly vertical throughout the year, and the mean temperature in these regions is correspondingly high; on the other hand, during the long polar night the sun is not seen for half the year, and very low temperatures prevail. There is thus a seasonal variation of the heat received from the sun in middle and high latitudes, the extent of which depends on the "obliquity of the ecliptic," i.e. the inclination of the earth's axis to the plane of its orbit round the

sun, and any changes in this factor must alter the seasonal variation of climate.

Further, since the climate of any place depends so closely on its latitude, it follows that if the latitude changes the climate will change. A ship can change its latitude at will, but we are accustomed to regard the position of the "firm ground beneath our feet" relatively to the poles as fixed within narrow limits. This stability has, however, been questioned from time to time, mainly on evidence derived from palæoclimatology, and theories of climatic change have been based on the wanderings of continents and oceans. Finally, local climate is intimately bound up with the distribution of land and sea, and the marine and atmospheric currents resulting therefrom, and on elevation above sea level, both of which factors, as we shall see, have suffered very wide variations in the geological past.

Nearly all the theories which have been put forward to account for geological changes of climate, and especially the occurrence of the last or Quaternary Ice Age, are based on the abnormal variation of one or other of the above factors, and we may consider them briefly in turn. Very few have ever been taken seriously. In the first place, we can at once dismiss fluctuations in the radiation emitted by the sun as a cause of *great* changes of climate. It is true that many small fluctuations are traceable directly to this cause, such as the eleven-year periodicity of temperature and rainfall; but these fluctuations are, and must be, greater at the equator than at the poles, while the fall of temperature during the Glacial period reached its maximum near the poles and was least at the equator. Moreover, there is not the slightest direct evidence in support of such a theory, and it can only be admitted when all other hypotheses have failed.

The "astronomical" theory of the cause of climatic fluctuations is associated chiefly with the name of James Croll. Croll's theory connects abnormal variations of

climate with variations, firstly of the eccentricity of the earth's orbit, and secondly of the ecliptic. In periods of high eccentricity the hemisphere with winter in aphelion is cold because the long severe winter is far from being balanced by the short hot summer; at the same time the opposite hemisphere enjoys a mild equable climate. This theory commanded instant respect, and still finds a place in the text-books, but difficulties soon began to appear. The evidence strongly suggests that glacial periods did not alternate in the two hemispheres, but were simultaneous over the whole earth; even on the equator the snow-line was brought low down. Moreover, on Mars the largest snow-cap appears on the hemisphere with its winter in perihelion. Although Croll's reasoning was beautifully ingenious he gave very few figures; while the date which he gives for the conclusion of the Ice Age, 80,000 years ago, has been shown by recent research to be far too remote, 15,000 years being nearer the mark.

Croll's theory has recently been revived in an altered form by R. Spitaler, a Czecho-Slovakian meteorologist, who calculated the probable alteration in the mean temperature of each latitude under maximum eccentricity (0.7775) and maximum obliquity (27° 48′), the distribution of land and water remaining unchanged. The results are shown in the attached table, where − means that the temperature was so much below the present mean, and + that it was so much above.

	Aphelion December.			Aphelion June.		
	Winter.	Summer.	Year.	Winter.	Summer.	Year.
	°F.	°F.	°F.	°F.	°F.	°F.
N. 60°	− 9	+15	−1	−5	−4	−1
30°	−13	+13	−2	+1	−8	−2
Equator	− 8	+ 4	−2	+1	−6	−2
S. 30°	− 6	+ 1	−2	+3	−5	−2
60°	− 2	− 1	−1	+1	−2	−1

Spitaler claims that these differences are sufficient to cause a glacial period in the hemisphere with winter in aphelion, but from this point his theory departs widely from Croll's. During the long severe winter great volumes of sea water are brought to a low temperature, and, owing to their greater weight, sink to the bottom of the ocean, where they remain cold and accumulate from year to year. But the water warmed during the short hot summer remains on the surface, where its heat is dissipated by evaporation and radiation. Thus, throughout the cold period, lasting about 10,000 years, the ocean in that hemisphere is steadily growing colder, and this mass of cold water is sufficient to maintain a low temperature through the whole of the following period of 10,000 years with winter in perihelion, which would otherwise be a genial interval. In this way a period of great eccentricity becomes a glacial period over the whole earth, but with crests of maximum intensity alternating in the two hemispheres. Unfortunately the numerical basis of this theory is not presented, and it seems incredible that a deficiency of temperature could be thus maintained through so long a period. Further, the difficulty about chronology remains, and the work brings the astronomical theory no nearer to being a solution of the Ice Age problem than was Croll's.

The theory which connects fluctuations of climate on a geological scale with changes in the composition of the earth's atmosphere is due to Tyndall and Arrhenius, and was elaborated by Chamberlin. The theory supposed that the earth's temperature is maintained by the "blanketing" effect of the carbon dioxide in the atmosphere. This acts like the glass of a greenhouse, allowing the sun's rays to enter unhindered, but absorbing the heat radiated from the earth's surface and returning some of it to the earth instead of letting it pass through to be lost in space. Consequently, any diminution in the amount of carbon dioxide present would cause the earth to radiate away its heat more freely, so reducing

its temperature. But it is now known that the terrestrial radiation which this gas is capable of absorbing is taken up equally readily by water-vapour, of which there is always sufficient present, and variations of carbon dioxide cannot have any appreciable effect.

Brief mention may be made here of a theory put forward by Humphreys, who attributed glaciation to the presence of great quantities of volcanic dust in the atmosphere. It would require an enormous output of volcanic dust to reduce the temperature sufficiently; but in any case the relation, if any, between vulcanicity and temperature during the geological ages is rather the reverse of that supposed by Humphreys, periods of maximum volcanic action coinciding more frequently with high temperatures than with low. Perhaps the best comment on Humphreys' theory is that in 1902 F. Frech produced its exact opposite, warm periods being associated with an excess of vulcanicity and cold periods with a diminution.

The theory which attributes climatic changes in various countries to variations in the position of the poles has been adduced in two main forms. The first is known as the Pendulation Theory, and supposes the existence of two "oscillation poles" in Ecuador and Sumatra. The latitude of these points remains unchanged, and the geographical poles swing backwards and forwards along the meridian of 10 E. midway between them. Varying distances from the pole cause changes of climate, and the movements of the ocean, which adjusts itself to the change of pole more rapidly than the land, causes the great transgressions and regressions of the sea and the elevation and subsidence of the land.

An alternative form put forward by P. Kreichgauer, and recently brought up again by Wegener, explains the apparent variations in the position of the pole, not through a motion of the earth's axis, but by the assumption that the firm crust has moved over the earth's core

so that the axis, remaining firm in its position, passes through different points of the earth's crust. The cause of these movements is the centrifugal force of the great masses of the continents, which are distributed symmetrically about the earth. Imagine a single large continent resting on a sub-fluid magma in temperate latitudes. Centrifugal force acting on this continent tends to drive it towards the equator. There is thus a tendency for the latitude of Europe to decrease. Similar forces acting through geological ages have caused the poles and equator to wander at large over the earth's surface, and also caused the continents to shift their positions relatively to one another. According to Wegener, in the Oligocene there was only a single enormous continent, America being united to Europe and Africa on the one hand, and through Antarctica to Australia on the other; while the Deccan stretched south-westwards nearly to Africa. The poles were in Alaska and north of the Falkland Islands. The treatment in Kreichgauer's original book is speculative and at times fanciful; Wegener's treatise appears to demand more respectful attention, but is open to some vital objections. In the first place, theories of this class demand that the glaciation occurred in different regions at widely different times, whereas we shall see in the following pages that the evidence points very strongly to a double glaciation during the Quaternary occurring simultaneously over the whole earth. This objection, which was fatal to Croll's theory in its original form, is equally fatal to theories of pole-wandering as an explanation of the Quaternary Ice Age. Secondly, we know that the last phase of this glaciation, known as the Wisconsin stage in America and the Wurmian in Europe, was highly developed only 20,000 years ago, and probably reached its maximum not more than 30,000 years ago. In the last 5000 years there has been no appreciable change of latitude, at least in Eurasia; and it seems impossible for the extensive alterations required in the

geography of the world by Wegener's theory to have taken place in so short a time.

The great glaciation of the Permian period, referred to in the next chapter, is a totally different matter. During this time the ice-sheets appear to have reached their maximum area, and to have extended to sea-level, in countries which are at present close to the equator, while lands now in high latitudes remained unglaciated. It is true that at the present day glaciers exist at high latitudes under the equator itself, and given a ridge sufficiently steep and a snowfall sufficiently heavy such glaciers would possibly extend to sea-level; but even these conditions would not give rise to the enormous deposits of true boulder-clay which have been discovered, and there seems no way of avoiding the supposition of an enormous difference in the position of the pole relatively to the continents at this time.

Wegener's theory alone, however, requires that glaciation should always have been proceeding in some part of the globe (unless both poles were surrounded by wide expanses of ocean), which is hard to reconcile with the extremely definite and limited glaciations which geological research has demonstrated. In these circumstances we may tentatively explain the pre-Tertiary glacial periods by combining Wegener's theory of the movements of continents and oceans as a whole with the theory of changes of elevation and of land and sea distribution which is outlined below. That is to say, we may suppose that the positions of the continents and oceans have changed, relatively both to each other and to the poles, slowly but more or less continuously throughout geological time; while at certain periods the land and sea distribution became favourable for extensive glaciation of the regions which at that time were in high latitudes.

The geographical theory, which states that the Ice Age was brought about by elevation in high latitudes, and by changes in the land and sea distribution, though

never seriously challenged, has suffered until recently from a lack of precision. The present author attempted to remedy this by a close mathematical study of the relation of temperature to land and sea distribution at the present day. The method at attack was as follows: from the best available isothermal charts of all countries the mean temperature reduced to sea-level was read off for each intersection of a ten-degree square of latitude and longitude, for January and July, from 70° N. to 60° S. latitude; this gave 504 values of temperature for each of these months. Round each point was next drawn a circle with an angular radius of ten degrees, divided into east and west semicircles. The area of each semicircle was taken as 100, and by means of squared paper the percentage of land to the east and land to the west were calculated; finally, in each month the percentage of the whole circle occupied by land, ice, or frozen sea was calculated, this figure naturally being greater in winter than in summer. The projection used was that of the "octagonal globe," published by the Meteorological Office, which shows the world in five sections, the error nowhere exceeding six per cent.

These figures were then analysed mathematically, and from them the effects on temperature of land to the east, land to the west, and ice were calculated. The detailed numerical results are set out in an Appendix; it is sufficient here to give the following general conclusions:

(1) In winter the effect of land to the west is always to lower temperature.

(2) In winter the effect of land to the east is almost negligible, that is to say, the eastern shore of a continent is almost as cold as the centre of the continent. The only important exception to this rule is 70° N., which may be considered as coming within a belt of polar east winds.

(3) In summer the general effect of land, whether to the east or west, is to raise temperature, but the effect

is nowhere anything like so marked as the opposite effect in winter.

(4) The effect of ice is always to lower temperature.

(5) For every latitude a "basal temperature" can be found. This is the temperature found near the centre of an ocean in that latitude. This "basal temperature" is a function of the amount of land in the belt of latitude. Poleward of latitude 20° an increase of land in the belt lowers the winter basal temperatures very rapidly and raises the summer basal temperature to a less extent. The "basal temperature" is important, since it is the datum line from which we set out to calculate the winter and summer temperatures of any point, by the addition or subtraction of figures representing the local effect of land in a neighbouring 10° circle.

As an illustration of the scale of the temperature variations which may be due to geographical changes, suppose that the belt between 50° and 70° N. is entirely above the sea. Then we have the following theoretical temperatures; for a point on 60° N. at sea-level:

January −30° F.; July 72° F.

Data for calculating the effect of ice are rather scanty, but the following probable figures can be given, supposing that the belt in question were entirely ice-covered:

January −30° F. (as for land); July 23° F.

Supposing that the belt were entirely oceanic, the mean temperature in 60° N. would be:

January 29° F.; July 41° F.

These figures show how enormously effective the land and sea distribution really is. From Appendix it is easy to calculate the probable temperature distribution resulting from any arrangement of land and water masses. Since the geography of the more recent geological periods is now known in some detail, we have thus a means of restoring past climates and discussing the distribution of animals and plants in the light of this knowledge. Of course it is not pretended that no other possible causes of great climatic variation exist, but no

others capable of seriously modifying temperature over long periods are known to have been in operation. As we shall see later, there are solar and other astronomical causes capable of modifying climate slightly for a few decades or even centuries, but these are insignificant compared with the mighty fluctuations of geological time.

In applying the results of this "continentality" study to former geological periods the method adopted is that of differences. The present climate is taken as a standard, and the temperatures of, for instance, the Glacial period are calculated by adding to or subtracting from the present temperatures amounts calculated from the change in the land and sea distribution. This has the advantage of conserving the present local peculiarities, such as those due to the presence of the Gulf Drift, but such a procedure would be inapplicable for a totally different land and sea distribution, such as prevailed during the Carboniferous period. That it is applicable for the Quaternary is perhaps best shown by the following comparison of temperatures calculated from the distribution of land, sea and ice with the actual temperatures of the Ice Age as estimated by various authorities (inferred fall):

Locality.	Author.	Inferred Fall.	Calculated Fall.		
			Jan.	July.	Mean.
		°F.	°F.	°F.	°F.
Scandinavia	J. Geikie	More than 20	36	18	27
East Anglia	C. Reid	20	18	13	15
Alps	Penck and Brückner	11	13	9	11
Japan	Simotomai	7	9	5	7

It is seen that the agreement is quite good.

There is one other point to consider, the effect of height. The existence of a great land-mass generally implies that part of it at least has a considerable elevation,

perhaps 10,000 or 20,000 feet, and these high lands have a very different climate to the neighbouring lowlands. Meteorologists have measured this difference in the case of temperature and found that the average fall with height is at the rate of 1° F. in 300 feet. In the lower levels the fall is usually greater in summer than in winter, but at 3000 feet it is fairly uniform throughout the year. Consequently, quite apart from any change in climate due to the increased land area, an elevation of 3000 feet would result in a fall of temperature of 10° F., winter and summer alike. This reinforces the effect of increased land area and aids in the development of ice-sheets or glaciers.

The effect of geographical changes on the distribution of rainfall are much more complicated. The open sea is the great source of the water vapour in the atmosphere, and since evaporation is very much greater in the hot than in the cold parts of the globe, for considerable precipitation over the world as a whole there must be large water areas in the Tropics. In temperate latitudes the water vapour is carried over the land by onshore winds, and some of it is precipitated where the air is forced to rise along the slopes of hills or mountains. Some rain falls in thunderstorms and similar local showers, but the greater part of the rain in most temperate countries is associated with the passage of "depressions." These are our familiar wind- and rain-storms; a depression consists essentially of winds blowing in an anti-clockwise direction round an area of low pressure.

These centres of low pressure move about more or less irregularly, but almost invariably from west to east in the temperate regions. They are usually generated over seas or oceans, and, since a supply of moist air is essential for their continued existence, they tend to keep to the neighbourhood of water masses or, failing that, of large river valleys. In a large dry area depressions weaken or disappear. Their tracks are also very largely governed by the positions of areas of high pressure or anticyclones,

which they tend to avoid, moving from west to east on the polar side of a large anticyclone and from east to west on the equatorial side. Since anticyclones are developed over the great land areas in winter, this further restricts the paths of depressions to the neighbourhood of the oceans at that season.

For all these reasons the tracks of depressions, and therefore the rainfall, are intimately connected with the distribution of land and sea. In winter there is little rainfall in the interior of a great land mass, except where it is penetrated by an arm of the sea like the Mediterranean; on the other hand, the coasts receive a great deal of rain or snow. The interior receives its rain mostly in spring or summer; if the coastal lands are of no great elevation this will be plentiful, but if the coasts are mountainous the interior will be arid, like the central basins of Asia.

The development of an ice-sheet is equivalent to introducing perpetual winter in the area occupied by the ice. The low temperature maintains high pressure, and storm tracks are unable to cross the ice. At the present day depressions rarely penetrate beyond the outer fringe of the Antarctic continent, and only the southern extremity of Greenland is affected by them. Since the total energy in the atmosphere is increased by the presence of an ice-sheet, which affords a greater contrast of temperature between cold pole and equator, storms will increase in frequency and their tracks must be crowded together on the equatorial side of the ice-sheet. In the southern hemisphere we have great storminess in the "roaring forties"; south of Greenland the Newfoundland banks are a region of great storminess. Hence, when an ice-sheet covered northern and central Europe the Mediterranean region must have had a marked increase of storminess with probably rain in summer as well as in winter.

But if snow-bearing depressions cannot penetrate an ice-sheet, it may be asked how the ice-sheet can live. The answer depends on the nature of the underlying

country. A land of high relief such as Antarctica is, and as Greenland probably is, rising to a maximum elevation of many thousand feet near its centre, draws its nourishment chiefly from the upper currents which flow inward on all sides to replace the cooled air which flows outwards near the surface. These upper currents carry a certain amount of moisture, partly in the form of vapour, but partly condensed as cirrus and even cumulus cloud.

At low temperatures air is able to hold only a negligible amount of water vapour, and this current, coming in contact with the extremely cold surface of the ice, is sucked dry, and its moisture added to the ice-sheet. Probably there is little true snowfall, but the condensation takes place chiefly close to the surface, forming a frozen mist resembling the "ice-mist" of Siberia. Even if the central land is not high enough to reach into the upper current at its normal level, the surface outflow of cold air will draw the current down to the level of the ice. This will warm it by compression, but the ice-surface is so cold that such warming makes little difference in the end. This process of condensation ensures that after the ice reaches a certain thickness it becomes independent of topography, and in fact the centre of the Scandinavian ice-sheet lay not along the mountain axis, but some distance to the east of it.

It is probably only on the edges of the ice-sheet, and especially in areas of considerable local relief, that snowfall of the ordinary type takes place, associated with moist winds blowing in the front section of depressions which skirt the ice-edge. But when conditions are favourable this source of supply is sufficient to enable these local ice-sheets to maintain an independent life, merely fusing with the edges of the larger sheet where they meet. Examples of such local centres in Europe were the Irish and Scottish glaciers, and at a later stage the Lofoten glaciers of the west of Norway, and in America the Cordilleran glaciers of Columbia.

Penck and Brückner have demonstrated that in the Alps the increase of glaciation was due to a fall of temperature and not to an increase of snowfall. The argument is threefold: firstly, the lowering of the snow-line was uniform over the whole Alpine area, instead of being irregular as it would be if it depended on variations of snowfall; secondly, the area and depth of the parent snow-fields which fed the glaciers remained unchanged, hence the increased length of the glaciers must have been due to decreased melting below the snow-line, i.e. to lower temperatures; thirdly, the upper limit of tree-growth in Europe sank by about the same amount as the snow-line. The same conclusion holds for the great Scandinavian and North American ice-sheets, the extension of which was undoubtedly due to a great fall of temperature. In the case of the Alps the interesting point has come to light that the fall of temperature, though due in part to increased elevation, is mainly accounted for by the presence of the Scandinavian ice-sheet, which extended its influence for many miles beyond the actual limits of glaciation, so that its waxings and wanings are faithfully reproduced in those of the Alpine glaciers, even to the details of the final retreat after the last maximum.

It is only when we turn to tropical and sub-tropical regions that we find variations of temperature unable to account for increased glaciation. Not only were the changes of land and sea distribution on a very much smaller scale than further north, but the Appendix shows that the temperature value of a corresponding change of land area is also very much less. But the high inter-tropical mountains—the Andes and Kenya and Kilimanjaro in central Africa—which to-day bear glaciers, in Quaternary times carried much greater ones. We cannot call in a fall of temperature, for the reason above stated, and also because at lower levels there is no evidence of colder conditions. In the Glacial period the marine fauna was the same as to-day, and mountains

which now fall short of the snow-line by a few hundred feet were still unglaciated even then. The only alternative is increased snowfall on the higher mountains Fortunately this fits in well with meteorological theory. The rain and snowfall of tropical regions depends, first of all, on the evaporation over the oceans. But evaporation is profoundly influenced by the velocity of the wind; and the wind, which in the Tropics represents the strength of the atmospheric circulation, depends on the thermal gradient between the equator and the poles; since there is no evidence of any appreciable change of temperature over the Tropics as a whole, while there was a very great fall in cold-temperate and polar regions, the thermal gradient, and therefore, ultimately, the tropical and sub-tropical, rain and snowfall must have been very greatly increased. Hence the increased glaciation of high mountains near the equator, and hence also the evidence of "Pluvial periods" in the sub-tropical arid regions on either side of the equator.

Thus during Glacial periods we have:

(1) Elevation in high latitudes caused a great increase of land areas there.

(2) Both elevation and increase of land area resulted in a lowering of temperature, materially increased by the gradual development of great ice-sheets.

(3) These ice-sheets caused the development of subsidiary ice-sheets on their southern and western borders.

(4) The lowering of temperature in high latitudes increased the thermal gradient between equator and poles, resulting in:

- (*a*) Increased snowfall, and hence increased glaciation on high mountains near the equator.
- (*b*) Pluvial periods in the sub-tropical arid regions.

BIBLIOGRAPHY

Humphreys, W. J. "Physics of the air." Philadelphia, 1920. [Pt. 4, pp. 556–629.]

Chamberlin, T. C. "An attempt to frame a working hypothesis of the cause of glacial periods on an atmospheric basis." *Journal of Geology* (American), Vol. 7, 1899, pp. 545–84, 667–85, 751–87. [Carbon di-oxide theory.]

Croll, J. "Climate and time in their geological relations." London, 1875. "Discussions on climate and cosmology." London, 1889. [Eccentricity of earth's orbit.]

Spitaler, R. "Das Klima des Eiszeitalters." Prag, 1921. Lithographed. [Eccentricity of earth's orbit. Reviewed in the *Meteorological Magazine*, London, September, 1921.]

Simroth, H. "Die Pendulationstheorie." Leipzig, 1908.

Kreichgauer, P. "Die Aequatorfrage in der Geologie." Steyr, 1902.

Wegener, A. "Die Entstehung der Continente und Ozeane." *Die Wissenschaft*, Bd. 66, Braunschweig, 1920.

Köppen, W. "Ueber Aenderungen der geographischen Breiten und des Klimas in geologischer Zeit." Stockholm, *Geografiska Annaler*, 2, 1920, p. 285–99.

Brooks, C. E. P. "Continentality and temperature." *Quarterly Journal of Royal Meteorological Society*, Vol. 43, 1917, p. 169; and 44, 1918, p. 253. [Influence of land and sea distribution.]

Enquist, F. "Eine Theorie über die Ursache der Eiszeit und die geographischen Konsequenzen derselbe." *Bull. Geol. Inst.*, Upsala, 13, 1915, No. 2. [Influence of land and sea distribution.]

Hobbs, W. H. "Characteristics of existing glaciers." New York, 1911. [Glacial anticyclone.]

TABLE OF GEOLOGICAL FORMATIONS

QUATERNARY	Recent Pleistocene
TERTIARY OF CAINOZOIC	Pliocene Miocene Oligocene Eocene
MESOZOIC OR SECONDARY	Cretaceous Jurassic Triassic
PALÆOZOIC	Permian Carboniferous Devonian Silurian Ordovician Cambrian
PROTEROZOIC	Pre-Cambrian

CHAPTER II

THE CLIMATIC RECORD AS A WHOLE

It is a remarkable fact that one of the oldest known sedimentary rocks is glacial in origin, and indicated the presence of an ice-sheet at a very early stage in the earth's history. This is a "tillite," or boulder-clay, discovered by Prof. Coleman at the base of the Lower Huronian (Early Proterozoic) of Canada. It extends in an east and west direction for 1000 miles across northern Ontario, and northward from the northern shore of Lake Huron for 750 miles. It rests on a scratched or polished surface of various rocks, and the included boulders are not always local, but some have been brought from a considerable distance. All these characters point to a large ice-sheet.

Traces of Proterozoic glaciations have been discovered in various other parts of the world, and some of these may be of the same age as the Canadian ice-sheet, but they cannot yet be dated exactly. An interesting example is western Scotland, which J. Geikie considered to have been glaciated by ice from the north-west which has since sunk into the North Atlantic. Other glacial remains have no doubt been destroyed or deeply buried, while some may still await discovery, and at present we must be content to note the occurrence of a glacial period at this time without attempting any description of the distribution of climates over the globe.

Followed a long period of milder climate indicated in America by thick deposits of limestone with the remains of reef-building organisms and other marine life. This

period may have been interrupted at least once by the recurrence of glacial conditions, but the evidence for this is doubtful. It must be remembered that the duration of the Proterozoic was very great, at least as long as all subsequent time, while the relics of it which are now known to us are few and scattered, so that much which happened during that time is a closed book. It is not until the very close of the Proterozoic that we again find indisputable evidence of widespread glacial action.

This second great glaciation was placed originally in the earliest Cambrian (see table of geological formations at the end of Chapter I), but later evidence shows that it is slightly older than the oldest deposit which can be referred to this series, and it may be designated the Pre-Cambrian glaciation. Tillites of this age have been found in the middle Yangtse region of China and in South Australia (where they extend from 20 miles south of Adelaide to 440 miles north, with an east-west extension of 200 miles). Glacial deposits which probably refer to this period have been found also in India, both in the Deccan and near Simla, over a wide area in South Africa, and in the extreme north of Norway. This distribution suggests the presence of two centres of glaciation, one between China, India and Australia, and the other north-west of Europe. The south-eastern of these was the most extensive, and probably indicates a ring of glaciated continents surrounding the pole, rather than a single enormous ice-sheet.

During the Cambrian all evidence of glacial action ceases, and we have, instead, evidence of a warm, fairly uniform climate in the abundant marine life. This continued during the Ordovician and became accentuated during the Silurian period, when reef corals lived in the seas of all parts of the world. Terrestrial deposits are curiously lacking in all this series, and this suggests that in the absence of any great mountain building and elevation shallow seas extended over almost the whole

of the surface, accompanied by mild oceanic climates extending to high latitudes.

At the close of the Silurian there was a period of mountain building and the formation of continents. The extinction of numerous species of marine organisms and the rapid evolution of others point to the seas becoming cooler and the stress of life more acute. In the succeeding Devonian period there is evidence of glacial conditions in South Africa in the form of a thick series of quartzites with striated pebbles up to fifteen inches long, but no typical boulder-clay has been discovered. There are also some doubtful traces from England. The most noteworthy development of the Devonian in the British Isles is, however, a thick deposit of red sandstone (Old Red Sandstone) of the type that is formed in shallow lagoons or inclosed basins, and suggesting desert conditions, so that the rainfall of the British Isles was probably slight.

These continental conditions passed away towards the close of the Devonian period, and once again extensive warm oceans appear to have spread over a large part of the globe, associated with the development of reef-building corals. Climate continued warm and equable throughout the greater part of the Carboniferous. The important feature of this period is the great system of coal-beds which extends through North America and Europe to China, with northern and southern limits in 80° N. (north-east Greenland and Spitzbergen) and 15° S. (Zambesi River). Wegener, summing up the evidence, and considering especially the absence of annual rings in the trees, concludes that the coal-beds are the remains of the tropical rain-forest when the equator lay across Europe some 30 degrees north of its present position.

Towards the close of the Carboniferous period great mountain-building set in, resulting in the formation of the famous Gondwanaland, including south and central Africa, southern Asia, part of Australia and possibly

Brazil. From a consideration of the glacial evidence, however, it appears, as will be seen later, that this was probably a ring of neighbouring and partly adjoining land areas rather than a single enormous continent. At the same time the climate became cooler, and a hardier vegetation, known as the *Glossopteris* flora, developed in the southern hemisphere, including woody trees with annual rings indicating seasons. The large insects of the coal forests which did not undergo a metamorphosis were replaced by smaller types which did pass through such a stage; this change of habit is considered to be due to the winters having become severe, so that the insects learnt to hibernate through them. In the early Permian, Gondwanaland was occupied by great ice-sheets, remains of which in the form of tillites of great thickness, ice-worn surfaces and striated boulders have been found in South Africa, Belgian Congo, and Togoland, Tasmania and widely separated parts of Australia, peninsular and north-western India, and probably also Afghanistan. In India the glacial striæ show that the ice-sheet was moving north, while in South Africa it was moving south, i.e. away from the present equator in both cases. Widespread glacial remains have been found also in Brazil, northern Argentine and the Falkland Islands, and there are probable traces near Boston in North America, in Armenia, the Urals and the Alps, and possibly also in England.

Wegener's reconstruction of the geography of this period places the south pole a little to the south-east of South Africa, surrounded by a great continent composed of the junction of Africa, South America, Antarctica, Australia, and an extended Deccan added to by smoothing out the folds of the Himalayas. This great circumpolar continent he considers to have been the site of an immense ice-cap. The North Pole lay in the Pacific Ocean, so that almost all the remaining land areas enjoyed temperate or tropical climates.

It is admitted that this peculiar distribution of glacial

remains apparently necessitates a position of the pole somewhere near that described by Wegener, but the theory of a single polar ice-cap extending beyond 50° latitude on nearly all sides presents difficulties. From the mechanism of the supply of snow to an ice-sheet described in the preceding chapter it follows that, except close to the edges, all the moisture precipitated must be brought in by upper currents. But even if we take into account the increase in the strength of the atmospheric circulation due to the introduction of an ice-cap, there is a limit to the supply of moisture by this process. All such moisture has to cross the periphery, and with increasing radius; the number of square miles of area to each mile of periphery becomes greater, slowly at first, then more and more rapidly. We shall see in Chapter VIII that even the North American Quaternary ice-sheet became unwieldy from this cause, and suffered several changes of centre.

Hence it seems that the *rapprochement* of the continents in Permo-Carboniferous times need not have been so complete as Wegener supposes, the glacial phenomena being more readily explicable by a ring of continents surrounding a polar sea, as in the case of the Quaternary glaciation of the northern hemisphere. The local Permian glaciations of Europe and North America, some of which fell close to Wegener's equator, are easily explicable as due to mountain glaciers similar to those of Ruwenzori and other tropical mountains during the Quaternary. There were interglacial periods in South Africa, Brazil and New South Wales, which increase the resemblance between the Permian and Quaternary Ice Ages.

In Upper Permian times there was a widespread development of arid climates, especially in the present temperate parts of North America and Europe. Wegener attributes this to the northerly position of the equator bringing the sub-tropical desert belt (Sahara, Arizona) to these regions. In the Trias these conditions

gradually gave place to another period of widespread warm shallow seas, with abundant marine life and corals extending over a large part of the world, even to Arctic Alaska. In the United States there are the remains of the forests of this period, in which the tree-trunks show very little evidence of annual rings, indicating that the seasonal changes were slight, so that the climate had again become mild and oceanic.

In the Lias (Lower Jurassic), there was crustal movement and volcanic action accompanied by land-formation and a gradual lowering of temperature. There was a great reduction in the abundance and geographical range of corals, and most of the species of insects are of dwarf types. There is, however, no evidence of glacial action.

The Upper Jurassic period appears to have been warmer than the Lias. Insects of a large size and corals again attained a very wide distribution, but there is enough difference in the marine faunas of different regions to indicate a greater development of climatic zones than in the extremely oceanic periods such as the late Triassic. Schuchert points out that the plants of Louis Philippe Land in 63° S. are the same, even to species, as those of Yorkshire.

In the Cretaceous period the climate was at first similar to that of the Jurassic, and trees grew in Alaska, Greenland and Spitzbergen. These trees, however, show marked annual rings, indicating a considerable differentiation of seasons, while trees of this age found in Egypt are devoid of rings. Towards the close of the Cretaceous there were many crustal movements and great volcanic outbursts, accompanied by a considerable reduction of temperature, which led to the extinction of many forms of life and the rapid evolution of others. There is no evidence of glacial action during the Cretaceous, however, though at the beginning of the Eocene there was a local glaciation of the San Juan Mountains of Colorado. According to W. W. Atwood this glaciation was double, the first stage being of the Alpine mountain glacier type,

separated by an interglacial from the second stage, which was of the Piedmont type (mountain glaciers spreading out on the plain at the foot of the mountain). This Eocene glaciation has been found nowhere else, however, and the climate of the Tertiary, which is discussed more fully in the next chapter, was in general warm and oceanic, becoming rigorous towards its close.

Summing up, we find that in the geological history of the earth two main types of climate seem to have alternated. Following on periods of great crustal movement, and the formation of large land areas, the general climate was cool, with a marked zonal distribution of temperature, culminating during at least four periods in the development of great sheets of inland ice. It is in such a period, though, fortunately, not at its worst, that we are living at present. During quiescent periods, on the other hand, when these continents largely disappeared beneath the sea, climate became mild and equable, and approached uniformity over a great part of the world. At these times, as soon as the surface water of the sea in high latitudes began to cool, it sank to the bottom, and its place was taken by warmer water from lower latitudes. The oceanic circulation was very complete, but there were practically no cold surface currents. Instead, there was probably a general drift of the surface waters from low to high latitudes (with an easterly trend owing to rotation of the earth), and a return drift of cooled water along the floor of the ocean. The formation of sea-ice near the poles became impossible, while the widespread distribution of marine life was facilitated.

The alternation of periods of crustal deformation with periods of quiescence has frequently been noticed, and has been termed the "geological rhythm." It may be attributed to the gradual accumulation of small strains during a quiescent period until the breaking point is reached, when earth-movements take place until equilibrium is restored, when the process is repeated.

The gradual erosion of the land by river and wave-

action and the consequent shifting of the load provides a certain amount of stress; but this is local, and calls for local readjustments only. A more generally effective agency may be the gradual slowing down of the earth's rotation under the influence of tidal friction. The mechanism of this process was described by A. E. H. Love ("Nature," 94, 1914, p. 254): "The surface of the ocean, apart from waves and tides, is at any time a figure of equilibrium answering to the speed of rotation at the time, more oblate when the speed is greater, less oblate when it is slower. Let us imagine that the lithosphere also is at some time a figure of equilibrium answering to the speed of rotation at that time. If the speed remained constant, the lithosphere would retain this figure, and the matter within it would remain always in the same configuration without having to support any internal tangential stress. Now suppose that the speed of rotation gradually diminishes. The surface of the ocean will gradually become less and less oblate. The lithosphere also will gradually become less oblate, but not to such an extent as to make it a figure of equilibrium answering to the diminished speed of rotation, while the matter within it will get into a state of gradually increasing internal tangential stress. The effect on the distribution of land and water will be that the depth of the ocean will gradually diminish in lower latitudes and increase in higher latitudes, the latitudes of no change being 35° 16′ N. and S.

"The internal tangential stress in the matter within the lithosphere may increase so much that it can no longer be supported. If this happens a series of local fractures will take place, continuing until the lithosphere is again adjusted much more nearly to a figure of equilibrium, which will be less oblate than the original figure. The effect on the distribution of land and water will be that the depth of the ocean will increase rather rapidly and spasmodically in lower latitudes and diminish in higher latitudes.

"Accordingly, the kind of geological change which the theory of tidal friction would lead us to expect is a sort of rhythmic sequence, involving long periods of comparative quiescence, marked by what Suess calls 'positive movements of the strand,' in the higher latitudes, and 'negative movements' in the lower, alternating with comparatively short periods of greater activity, marked by rise of the land around the poles and subsidences in the equatorial regions."

The main periods of adjustment under this scheme fall at the beginning and end of the Proterozoic, in the Permo-Carboniferous and in the Quaternary. The two latter at least were periods of great earth-movement, while the two former were also continental periods, since the land masses were large and high enough to develop ice-sheets.

The difficult question raised by the low latitudes in which the Pre-Cambrian and Permo-Carboniferous glaciations were chiefly developed cannot yet be regarded as solved, but the geological facts speak strongly in favour of ice-sheets rather than mountain glaciers, and practically speaking it is meteorologically impossible for large ice-sheets to extend to sea-level in the Tropics while the rest of the world enjoys a temperate climate. The only escape seems to be to assume a position of the South Pole somewhere between Africa, India and Australia throughout the whole of the Proterozoic and Palæozoic periods. On the other hand, from the Jurassic onwards, there is no real support to the hypothesis that the positions of the poles were other than they are now. Wegener's explanation of the Quaternary Ice Age we have seen to be untenable. The period of transition appears to lie in the later Permian and Triassic. The Proterozoic and Permo-Carboniferous glacial periods were much less definite in the north than in the south-east; but such as they were they appear to have been most severe in the east of North America, where the ice was coming from the north; there are also some glacial traces in Europe.

This indicates that the position of the North Pole cannot have been in the North Pacific Ocean, which is antipodal to the South Indian Ocean. Hence it seems that what we have to consider is not so much the wanderings of the poles at large among the continents as the break-off at the close of the Palæozoic period of portions of the Antarctic continent and their drift northwards towards the equator. Without going into the mathematics of the question, it seems just possible that the periodic overloading of circumpolar continents by large ice-masses could have this effect in the course of time,[1] but the suggestion is put forward tentatively for consideration rather than as a definite hypothesis. We must be thankful that in the next chapter we are on safer ground.

BIBLIOGRAPHY

Coleman, A. P. "Climates and physical conditions of the early Pre-Cambrian." *Geol. Mag.* (6), Vol. 1, 1914, p. 466.

Eckardt, W. R. "Paläoklimatologie." Sammlung Goschen, Leipzig, 1910.

Geikie, J. "The Evolution of Climate." Edinburgh, *Scot. Geogr. Mag.* (6), 1890, p. 57.

Grabau, A. W. "Principles of Stratigraphy." New York, 1913, pp. 74, *et seq.*

Neumayr, M. "Ueber klimatischen Zonen während der Jura- und Kreidezeit." Wien, *Denkschr. Ak. Sci.*, 47, 1883, p. 211.

Ramsay, W. "Orogenesis und Klima." *Ofvers af Finska Vetenskaps. Soc. Forh.*, 52, 1909–10, A, No. 11. Helsingfors, 1910.

Schuchert, C. "Climates of Geologic Time, In: The climatic factor as illustrated in arid America," by Ellsworth Huntington. Washington, 1914, Pt. 2.

[1] If the figure of the earth is adjusted to its speed of rotation before the development of ice-sheets, the latter renders it too prolate, and there will be a tendency for readjustment by the transference of mass towards the equator.

CHAPTER III

CONDITIONS BEFORE THE QUATERNARY ICE AGE

The third of the great periods into which the geological record is divided is known as the Tertiary. Throughout most of its length it appears to have been characterized by remarkably mild and equable climatic conditions extending into comparatively high latitudes, so that the west coast of Greenland, for instance, had a flora of almost sub-tropical aspect. Since the plants in question —chiefly palms and cycads—are not of identical species with their present-day representatives, it is unsafe to base numerical estimates of the temperature upon them, but it is at least obvious that these regions were warmer than they are at present.

Let us glance for a moment at the geography of the Tertiary period. The most noticeable point is a great expanse of sea over south-eastern Europe, including the Mediterranean countries, extending away over the Black Sea and Caspian, and stretching in a great arm to the Arctic Ocean, south of Novaya Zemlya. The geology of the archipelago north of Canada is not yet well known, but it seems probable that there was a considerable area of Tertiary ocean there also. The sea further encroached on the present boundaries of North America, both east and west, and on the north-eastern coast of Asia. Bearing in mind the principles set out in the first chapter, we can infer from these changes a great increase in the winter temperature of the regions along the Arctic circle. The increase reached a maximum on the west of Greenland and in western Siberia, but

the west coast of Alaska also had a decidedly warm climate in the late Miocene and Pliocene.

The basin of the Arctic Ocean, which already existed at that stage, was raised to a temperature considerably higher than the present by three great streams of warm water flowing into it. If, as seems probable, the Bering Strait was deeper, and the submarine ridge across the North Atlantic less pronounced, the obstacles to the outflow of cold water along the ocean floor were much less than now. Finally, the winter temperatures of the land masses to the south, and especially Siberia, being already very much less severe owing to the sea over Europe, the temperature of the water of the great rivers flowing into the Arctic was not so low. For these reasons the development of ice in the Arctic Ocean was very much diminished, and possibly entirely absent, allowing a great amelioration of the climate of Greenland, the rigor of which is at present much enhanced by the ice which flows down the Greenland Sea and round Cape Farewell.

The cumulative effect of all these changes—greater water area, greater inflow of warm surface water, less inflow of cold river water, less ice-development—must have been a mild equable rainy climate, entirely suitable to a rich vegetation. The sub-tropical aspect of that vegetation should not be stressed, for it was probably as much an expression of the geological age of the period in question as of its climate.

The objection may be raised that at the present time the sub-antarctic islands in the great Southern Ocean have the most maritime climate in the world, but are not by any means places of opulent vegetation. The difference is entirely accounted for by the presence of the great ice-bearing Antarctic continent. Its effect is twofold. Firstly, the glaciers shed into the Southern Ocean an immense quantity of ice and ice-cold water annually, which must have an appreciable effect on temperature. Secondly, the presence of this ice-covered

continent and the floating ice in its neighbourhood extending as far as the sixtieth parallel, by forming a marked contrast with the warmer waters further north, greatly intensifies the strength of the atmospheric circulation in these regions, resulting in the development of a great succession of severe storms which sweep the sub-antarctic islands. There are no great land-masses to break the force of the wind, and these latitudes are among the stormiest, windiest regions of the earth—gale succeeding gale, winter and summer alike; and it is largely to the extraordinary power of the wind that we must attribute the desolate appearance of the islands.

The picture we have drawn of the high northern latitudes in early Tertiary times is vastly different. A great warm ocean occupied the Arctic regions, fed by three ocean currents analogous to the Gulf Drift, and the fall of temperature was gradual from the tropic to the pole. The return colder currents were mainly along the ocean floor and with little ice-formation the storms were few and not severe. On the western shores of the continents mild rain-bearing south-west winds prevailed, and a quiet moist warm atmosphere existed which was especially favourable to plant life. This favourable state of affairs lasted until well on in the Miocene, and then changes set in. The land and sea distribution underwent essential modifications. The great Tertiary continent or archipelago which is believed to have existed in the western Pacific, and whose last remaining summits now form the scattered islands of that ocean, gradually subsided, and in its place elevation began in higher latitudes. Bering Strait became narrow and shallow, and was probably for a time entirely closed, while the connexion between the Arctic and Indian Oceans was closed permanently, leaving in its lowest areas a chain of great inland seas and lakes, of which the Caspian and Aral Seas are now the greatest representatives. The Canadian Archipelago was probably raised above its present level, and formed a great northern extension of

the American continental area. The changes in the Atlantic also were very extensive. The West Indies were the site of a large and lofty Antillean continent; further north a considerable land-mass existed east of Newfoundland; Greenland was joined on the west to the extended American continent, and considerably enlarged to the south-east. Iceland, though it remained an island, was elevated and probably nearly doubled in area, and between Iceland and the north of Scotland was developed a great submarine ridge, which may or may not have risen above the sea in places. The British Isles became a solid block of land, united with continental Europe across the English Channel and the great plain which is now the North Sea. Scandinavia was elevated by more than a thousand feet, and the elevation extended at least as far as Spitzbergen. The Murman area had a considerable extension. In eastern Asia the Sea of Okhotsk was land and Japan was united to the mainland.

In the southern hemisphere our knowledge is not nearly so detailed. The presence of marine Middle-Tertiary beds with temperate mollusca in Graham Land and of plant-bearing beds in Seymour Island point to a smaller Antarctic continent and very much warmer conditions at this time in the South as well as in the North Polar regions. For the close of the Tertiary, however, we have strong grounds in the distribution of animals and plants for assuming that the Antarctic continent was greatly increased in size, with promontories uniting it to Australia on the one hand and to South America on the other. New Zealand was largely increased in area, and South Africa probably extended further polewards. The sub-antarctic islands attained a much greater area. Conditions were ripe for the Ice Age in the southern as well as the northern hemisphere.

BIBLIOGRAPHY

Kerner von Marilaun, F. "Synthese der morphogenen Winterklimate Europas zur Tertiärzeit." Wien, *SitzBer. K. Akad. Wiss*, 122, 1913, pp. 233–98.

Osborn, H. F. "The age of mammals in Europe, Asia and North America." 8vo. New York, 1910.
Nathorst, A. G. "On the fossil floras of the Arctic regions as evidence of geological climates." London, *Bot. J.* 2, 1913, pp. 197–202; and Washington, *Report Smithsonian Inst.*, 1911.
Dall, W. H. "On climatic conditions at Nome, Alaska, during the Pliocene." *Amer. J. Sci.*, ser. 4, Vol. 23, 1907, p. 457.
Nansen, F. "The bathymetrical features of the North Polar seas, with a discussion of the continental shelves and previous oscillations of the shore-line." *Norwegian N. Polar Exped.*, 1893–96. *Scientific Results*, Vol. 4.
Spencer, J. W. "Reconstruction of the Antillean continent." *Bull. Amer. Geol. Soc.*, 6, 1895, pp. 103–40.
Wilckens, D. "Die Mollusken der antarktischen Tertiärformation." *Wiss. Ergebn. der Schwed. Sudpolar Exped.*, 1901–3, Bd. 3, 1911.
Hedley, C. "The palæographical relations of Antarctica." London, *Proc. Linnæan Soc.*, 124, 1911–2, p. 80.

CHAPTER IV

THE GREAT ICE AGE

As the land began to rise, the first effect was an increased snowfall on the higher summits, and increased rainfall on the rising coast lands. The rivers had an increasing fall towards the sea, and rapidly carved out deep narrow valleys, which were later developed by the ice into the great fiords of Norway and other heavily glaciated regions. But on the whole the first beginnings of the Ice Age occurring towards the close of the Pliocene period are obscure, and are likely always to remain so, for the simple reason that the advancing and retreating ice-sheets have wiped out most of the evidence of the conditions which immediately preceded their advent. The deteriorations of the climate had begun long before the geographical changes outlined at the close of the last chapter were complete, for mollusca of the Pliocene beds in East Anglia indicate progressive refrigeration of the North Sea at the same time as it became increasingly shallow. At the close we have great shell-banks with northern species which must have been piled up by powerful easterly winds ; these easterly winds show that the storm tracks had been driven south of their present course and suggest that the glacial anticyclone already existed over Scandinavia. At the present day similar shell-banks are forming on the coast of Holland under the influence of the prevailing westerly winds. The next series of deposits in this region are fresh-water "forest beds," attributed to a greatly extended Rhine,

and belong to the period when the North Sea had become a plain.

It is no part of the plan of this work to go over the geological ground of the Quaternary Ice Age, which has already been so frequently and so efficiently covered. All I can hope to do is to give a brief general account of the succession of climatic changes involved, necessarily incomplete since so much of the world is at present insufficiently explored for glacial traces. But a certain amount of explanatory introduction is necessary.

In Europe and North America there are distinct traces of several separate glaciations with "interglacial" periods when the climate approached or became even warmer than the present. The time-relations of these glaciations are not yet fully worked out, but there seems little doubt that they were contemporaneous in the two continents. The correlation is not perfect, however, since the United States geologists recognized altogether five glaciations. The explanation appears to be that the equivalent of the Rissian glaciation in America is double; two stages, the Illinoian and Iowan, being recognizable, separated by a retreat of the ice. The series is as follows:

Alps.	Northern Europe.	North America.	Date. B.C.
I Gunz	?	Jerseyan or Nebraskan	?
II Mindel	Lower Diluvium	Kansan - -	430,000–370,000
III Riss	Middle Diluvium	Illinoian / Iowan - -	130,000–100,000
IV Wurm	Upper Diluvium	Wisconsin - -	40,000– 18,000

The correlation is based on the amount of weathering and erosion which the various deposits have undergone. The time which has elapsed since the glaciers of the last or Wurm stage were in active retreat has been estimated by comparing the growth of peat-bogs, river-deltas, etc.,

during historical times with that since the last retreat of the ice. But the most conclusive method is due to the Swedish geologist Baron de Geer, who has actually counted the years since the ice in its final retreat left any particular point between Ragunda and the south of Sweden. The work is based on the idea that the lamination observed in certain marine and lacustrine clays in Sweden is seasonal, the thick coarse layers being due to the floods produced by the rapid melting of the ice in summer, and the thinner and finer layers being due to the partial cessation of melting in winter. By correlating one section with another it is possible to date any particular layer with great exactness, and further to prove the existence of several great climatic fluctuations during the retreat. The topmost limit of the section is given by the surface of the old floor of Lake Ragunda in Jemtland, which received its waters from one of the permanent glaciers and was accidentally drained in 1796. De Geer finds that the edge of the last great ice-sheets lay over southern Scania about 12,000 years ago, and further estimates 8000 years for the retreat across the Baltic. These results are in general agreement with those obtained by other methods, and we may accordingly, with some confidence, put the date when the ice-sheet of the Wurm glaciation finally left the coast of Germany at about 18000 B.C.

This period fixed, we have a datum for estimating the duration of the interglacial periods. The moraines of the Wurm glaciation present everywhere a very fresh appearance, and the chemical change which the boulders they contain have undergone is slight, while weathering extends to a depth of scarcely a foot. The moraines of the Riss glaciation are weathered somewhat more deeply, and those of the Mindel glaciation very much more. Assuming that chemical weathering has proceeded uniformly during the interglacial periods and ceased during the glaciations, Penck and Brückner, who have studied exhaustively the glaciation of the Alps, find that

the Riss-Wurm interglacial lasted about three times as long as the interval between the Wurm glaciation and the present day, or 60,000 years, and the Mindel-Riss interglacial about twelve times as long, or 240,000 years. No data are available for the Gunz-Mindel interglacial, but it is provisionally made equal to the Riss-Wurm, another 60,000 years.

No possibility of such direct measurement of the duration of the glacial periods themselves has yet been found. Penck and Brückner assume that the duration equalled that of the Riss-Wurm interglacial, or 60,000 years in each case. This seems unnecessarily long. The Yoldia Sea, the deepest part of which coincided with the centre of the Scandinavian glaciation, appears to have reached its greatest depth not more than 6000 years after the maximum of glaciation, indicating a lag of this period. The subsidence of the land due to the weight of the ice-sheet may have commenced some time before the maximum of glaciation, but the duration of the subsidence can hardly have been more than 10,000 years, and this is the limit for the second half of the Wurm glacial period. Further, we know that during the growth of the ice-sheets there was comparatively little melting, for the rivers then had little power of carrying debris. Recent measurements in Greenland give the rate of ice-growth on the surface of the ice-sheet as 40 cm., or 15 inches a year ; let us say a foot, and assume a marginal loss equivalent to half this amount over the whole ice-sheet. This gives us an average increase of six inches a year, or 10,000 years for growth to a maximum thickness of 5000 feet. On these grounds the estimated duration of the Rissian glacial period has been reduced to 30,000 years, and that of the Wurm period to 22,000 years. Only in the case of the long and complicated Mindelian period, which, as will be seen later, was virtually a series of overlapping glaciations from various centres, has the figure of 60,000 years been accepted. In the present state of our knowledge no estimate of the

duration of the Gunz-Mindel interglacial can have any value, and the dates are accordingly carried back only to the Mindelian. In this way we obtain the time-scale given on page 48.

The fourfold glaciation has been recognized with certainty only in Europe and North America, and even in these countries there is considerable doubt whether the northern ice-sheets shrank back as far as their present narrow limits during the interglacial periods. The long Mindel-Riss interglacial, which was probably the Chellean stage of flint industry,[1] was characterized by a very warmth-loving fauna, and it is possible, even probable, that during this period the glaciers melted completely away, except on the very highest summits. Of the climate of the Gunz-Mindel interglacial (termed by J. Geikie the "Norfolkian," from the Cromer Forest Bed), we have comparatively little evidence. If the suggestion put forward in the following chapter is correct, the Gunz-Mindel interglacial was merely a local incident in the glaciation of the Alps, and not a true interglacial at all. Even the Cromer Forest Bed itself is not conclusive, since it is a river deposit largely composed of material drifted from lower latitudes. The Riss-Wurm interglacial (J. Geikie's "Neudeckian") nowhere gives us evidence of a climate as warm as the present, and as regards the Scandinavian and Canadian ice-sheets may have been merely an extensive and prolonged oscillation of the ice-edge.

As regards the glaciation of Norway, the question has been investigated recently by H. W. son Ahlmann, who has published a long and detailed paper in English in volumes 1 and 2 of the Swedish *Geographiska Annalen*. He concludes that the morphology of Norway, without reference to stratigraphical or biological data, gives conclusive evidence of two glaciations. The first of these was the greater, and between that time and the

[1] This has been the subject of much discussion recently. For a summary see *Science Progress*, 17, 1922, October, p. 233.

second smaller glaciations there occurred an interglacial period of such considerable length that the greater part of the present gorges was then formed by fluvial erosion.

We may, accordingly, consider the Ice Age as fourfold or double, according to the point of view from which we regard it. In the Alps and other mountain ranges on the borders of the great northern ice-sheets, which respond very readily to small changes, it was fourfold. In the peripheral regions of the northern ice-sheets themselves it has an appearance of being threefold or fourfold. In the more central regions of these great ice-sheets, where response to climatic change is very slow, there is no evidence of more than two glaciations; but in these regions, where the destructive effect of the ice reached its maximum, it is only by the merest chance that evidence of interglacial periods is preserved at all. And finally, in all other parts of the world we have evidence of only two glaciations at most.

There is one deposit which is of considerable importance in the study of interglacial climates, and that is the loess. Loess is an exceedingly fine-grained homogeneous deposit resulting from the gradual accumulation of wind-blown dust on a surface sparsely covered with vegetation. It is to be seen accumulating at the present day in parts of south-east Russia and central Asia. Its formation, except in closed basins, needs a climate of the steppe character, with not much rainfall, and especially with a long dry season. Now loess was very extensively developed in Europe during the Quaternary. Its occurrence is peculiar, since it is found most widely developed resting on the deposits of the Rissian glaciation, and is never found resting on the moraines of the Wurm glaciation. A little loess is found below the Riss moraines, and it has also been found between the Riss and Wurm moraines. In the pre-Rissian loess an implement of Acheulian age was discovered in 1910 at Achenheim

(Alsace), by R. R. Schmidt and P. Wernert, indicating that the deposit was formed towards the close of the Chellean industry, when the climate was already cold and dry. In the same section the younger loess seems to fill completely the Riss-Wurm interglacial, since Mousterian implements were found at the base and Aurignacian implements in the middle. The younger loess contains remains of the jerboa and other rodents at present inhabiting the Siberian steppes. It is therefore reasonable to conclude that steppe conditions prevailed in central Europe through practically the whole of the Riss-Wurm interglacial, and the same probably applies to the corresponding pre-Wisconsin interglacial in America. But if a steppe climate prevailed in central Germany there must have been very severe conditions in Scandinavia, and probably the ice-sheet maintained a quite considerable area there throughout the whole period, though without encroaching on the Baltic basin. In North America the loess was deposited by westerly winds, indicating that the ice-development was not sufficient to impose anticyclonic conditions in place of the present prevailing westerly winds, and the same appears to be true of Europe. Similar climatic conditions were developed for a short time at the close of the Wurm glaciation, but without any appreciable development of loess. (See Chapter XIII.)

BIBLIOGRAPHY

Wright, W. B. "The Quaternary Ice-age." London, Macmillan, 1914.

Brooks, C. E. P. "The correlation of the Quaternary deposits of the British Isles with those of the continent of Europe." *Ann. Rep. Smithsonian Inst.*, 1917, pp. 277–375.

de Geer, G. "A thermographical record of the late Quaternary climate." *Ber. Internat. Geologenkongr.*, Stockholm, 1910. "*Die Veränderungen des Klimas*," p. 303.

———. "A geochronology of the last 12,000 years." *Ber Internat. Geologenkongr.*, Stockholm, 1910, Vol. 1, p. 241.

Penck, A., and Brückner, E. "Die Alpen in Eiszeitalter." Leipzig, 3 Vols., 1901-9.
Ahlmann, H. W., son. "Geomorphological studies in Norway." Stockholm, *Geografiska Annaler*, 1, 1919, pp. 1–157, 193–252.
Richthofen, F. "On the mode of origin of the loess." *Geol. Mag.*, 1882, p. 293.

CHAPTER V

THE GLACIAL HISTORY OF NORTHERN AND CENTRAL EUROPE

The literature of the glacial period in Europe is stupendous and is, further, of a highly contradictory nature. Space does not permit of any summary of the great conflict between the monoglacialists and the polyglacialists; it is sufficient to say that the latter often went to extremes and so laid themselves open to defeat, but the twofold nature of the glaciation is now widely accepted. It must be understood, however, that the following summary represents the views of a certain section of geologists only, views which are not universally held. In the British Isles especially, where the remains of the maximum glaciation completely dominate those of all the others, the theory of a single glaciation still largely prevails.

When ice began to accumulate on the rising Scandinavian plateau it naturally formed at first on the Norwegian mountains near the Atlantic, which was the chief source of snowfall. These mountain glaciers spread rapidly down the steep seaward slopes to the west and more slowly down the gentler landward slopes to the east. At this stage the centre of the ice-sheet, and consequently the centre of the glacial anticyclone, as soon as the latter developed a definite existence, lay quite near the Norwegian coast. Under anticyclonic conditions the circulation of the winds round the centre is in the same direction as the motion of the hands of a watch, combined with an outward inclination at an angle of about thirty to forty-five degrees. Consequently, while the centre lay in Norway, due north of the Alps,

the prevailing winds in the latter must have been from north-east, and therefore very cold. Accordingly, this stage is probably contemporaneous with the Gunz glaciation of the Alps. In the same way, over the North Sea area the winds must have been easterly, causing the currents which piled up the great shell-banks of the East Anglian coast, already referred to as marking the end of the Tertiary and beginning of the Quaternary period.

But the ice which reached the northern North Sea broke up into icebergs not far from the coast, and floated away, while that which moved east into the north of Sweden could only be dissipated by melting and ablation, processes which we have reason to believe went on very slowly. Hence ice began to accumulate and spread over a wide area east of the main Scandinavian mountain chain. Fresh snow was deposited directly on this ice-surface, until it gradually overtopped the mountains which originally gave rise to it, and reversed the flow, so that the ice actually moved uphill across the mountain chain. As the centre of the ice-sheet moved eastward the glacial anticyclone moved with it, and this new position to the eastward caused an alteration in the direction of the prevailing winds over the rest of Europe. The Alps were now south-west of the anticyclonic centre, and the winds in that district accordingly became easterly instead of north-easterly. Of course, the glacial anticyclone was now more intense, but in summer in central Europe easterly winds are naturally so much warmer than north-easterly winds that at first this increase in intensity was not enough to counterbalance the change in direction, and there was a slight improvement in the Alpine climate. In the same way, over the North Sea district the prevailing winds had now become south-easterly instead of easterly, which would make for a slight rise of temperature, as also would the occasional depressions which would be able to make their way in from the westward, bringing warm moist air from

the Atlantic and occasional rainfall. By this time the process of elevation had converted the North Sea floor into an extensive plain.

From Sweden and the Gulf of Bothnia the ice spread out in all directions, extending in the east to the foot of the Ural Mountains, which formed an independent centre of glaciation; in the south-east over a large part of European Russia, where it reached as far south as latitude 40° in the Dnieper valley; in the south over almost the whole of Germany as far as the Riesengebirge and Harz Mountains; and in the south-east over the whole of Holland and the North Sea basin. It should be noted that Holland and Denmark were glaciated, not by Norwegian ice, but by ice from the Baltic sheet which had crossed southern Sweden. The North Sea glacier extended across East Anglia as far as Cambridge, while a northern branch of it swept across Caithness and the Orkney and Shetland Islands, but most of the British Isles were glaciated from independent centres—the Scottish Highlands, the Pennines, Cumberland, Wales and northern Ireland.

With the growth of the glaciated area, and particularly with its extension south-westward across the North Sea, the Alpine climate again became very severe, and the local glaciers and Piedmont ice-sheets of the Alps reached their maximum development in the Mindelian. At the same time the central plateau of France developed a local plateau glacier of its own, and the Pyrenees underwent their first and greatest glaciation, no traces of the Gunzian having been found in this range.

The British Isles show an interesting outward migration of the local centres of maximum ice-development. The Scandinavian glacier which invaded East Anglia extended arctic anticyclonic conditions across the North Sea, and induced a heavy snowfall over the high lands of Great Britain. These, in consequence, developed independent glaciers, which on their eastern sides fused with the Scandinavian glacier and, partly by deflecting its flow,

partly by intercepting some of its snowfall, pushed it back into the North Sea plain. The Scottish glaciers became strong enough to encroach on Ireland, partly in the north-east, and partly by way of the Irish Sea and St. George's Channel (then a valley) on to the south-east. This further extension of the cold area enabled the Irish glaciers to develop, and these in turn pushed back the Scottish glaciers until Ireland was solely glaciated by Irish ice.

The southern margin of the ice-sheet did not extend beyond the Thames valley, but at some stage the English Channel carried floating ice, which formed the deposits of ice-borne boulders, of which that at Selsey is a well-known example.

This great ice-sheet nowhere formed marked terminal moraines, but its deposits fade away in thin beds of stiff boulder-clay. This absence of moraines is probably connected with the great thickness of the ice-sheets, which did not leave any appreciable nunataks or rocky "islands" exposed in its path, so that there was nothing to give rise to detritus on the surface of the ice. All the transportation had to be carried on beneath the ice-sheets, and these, penetrating into comparatively low latitudes where the sun is powerful in summer, would suffer gradual melting and ablation for some distance from their margins. Near the actual ice-limit the motion must have been slow and the thickness of the ice small, so that conditions were against the accumulation of thick beds of detritus.

On the borders of the ice-sheet the climate cannot have been over-rigorous, for pre-Chellean man was able to live almost up to the ice-edge. The air must have been extremely cold, and there was a belt of high arctic climate round the ice, but in the south and south-west this appears to have been very narrow, and sub-arctic conditions, no worse than those in which many races live to-day, prevailed not very far from the ice. The configuration of the ice-surface largely explains this. A

high steeply sloping wall of ice causes intensely violent winds, carrying dense clouds of drift-snow—blizzards, in fact, similar to those now experienced in parts of Antarctica under similar circumstances, which sweep the land bare of all life for a considerable distance. But a low and gradually sloping surface, such as seems to have existed near the borders of the maximum glaciation, favours instead comparatively gentle winds without much drift snow. It is only on the north-west ice-ridge, where ice-cliffs fronted the sea and where severe storms from the Atlantic were frequent in winter, that blizzards occurred.

When the land in Scandinavia began to sink under the ice-load more rapidly than the supply of snow could build up the surface of the ice-sheet the force which pushed out the ice in all directions from the centre gradually died away, and the ice-masses over the North Sea area—now probably again below sea-level—and the low grounds of Europe were left derelict, with no resources but the snowfall on their own surfaces. Under these conditions they melted away more or less rapidly. While these derelict ice-masses were still large, the auxiliary peripheral centres in the Alps, Pyrenees and British Isles maintained an independent existence for a while, probably with fluctuations similar to those which marked the close of the last glaciation in the Alps, though the evidence of these has now been wiped away. It is even likely that the beginnings of the weakening of the central source of supply helped the British ice to divert the Scandinavian ice into the North Sea. Had there been any powerful rivers bearing great masses of detritus from the south, as there are in Siberia, some of these derelict ice-sheets might have been preserved for a time, at least, as "fossil ice," but in western Europe conditions were not favourable for this.

With the disappearance of the ice-sheets the general climate of Europe must have passed through a series of stages of amelioration, of which traces can be found here

and there, though the details are lost to us. Ultimately temperate conditions again prevailed; and for a very long time, approaching a quarter of a million years, Europe cannot have differed greatly from present climatic conditions. In Scandinavia the mammoth roamed in forests of birch, pine and spruce; further south the mammoth is absent, and we find instead more southern forms—*Elephas antiquus*, resembling the Indian elephant, *Rhinoceros merckii*, a southern form, the sabre-toothed tiger, cave-lion, cave-bear and cave-hyæna, wolf, beaver, horse and various forms of deer, while the flora included even such warmth-loving trees as the fig. Obviously, during part of this interglacial period, the climate must have been even warmer than the present.

Let us glance for a moment at the probable conditions. One of the dominant features in the present weather of Europe is the accumulation of floating ice in the Arctic basin. This keeps the temperature low and the pressure high—forms in fact during the spring and summer months a temporary glacial anticyclone similar in kind to, though of less intensity than, that which has been described as covering the Scandinavian ice-sheet. This anticyclone maintains on its southern edges a belt of easterly winds, and these winds enter into the general circulation of the earth. Their effect is to push southward the permanent storm-centres normally situated near Iceland and the Aleutian Islands, and it is these storm-centres which play a large part in causing the rainy weather of northern and central Europe. But occasionally—as in the remarkable spring and summer of 1921—these conditions break down. The Arctic Ocean becomes unusually ice-free and warm, the pressure falls, and in consequence the storm-centres move northward. Europe comes under the influence of the permanent anticyclones of sub-tropical latitudes, rain-bearing storms pass far to the northward, and we have a dry warm summer of the Mediterranean type.

This is presumably what happened during the long

warm Mindel-Riss interglacial. For some reason, possibly connected with a temporary widening and deepening of the Bering Strait, the waters of the Arctic Ocean became warmer and the amount of floating ice less. Pressure became lower in the polar basin and therefore higher over the Atlantic and Europe, and fine warm conditions prevailed in Europe as the normal climate instead of only as an occasional event.

This warm interval was finally brought to a close by the renewed elevation of Scandinavia, and the ice-sheets began to develop again, heralded by a period of dry steppe climate. This time, however, the conditions were different; the elevation was not so great, and was more local. Hence the resulting glaciation was less intense; it filled the Baltic basin and extended some distance on to the North German plain and into Holland. It failed to reach the coast of Britain, but that it extended some way across the North Sea plain is indicated by the peculiar distribution of the Newer Drift of Britain, to be referred to later. In the north of Norway the slope of the ice towards the sea was very steep, so that many of the coastal hills extended above it as nunataks. The ice extended into the channel between the mainland and the Lofoten Islands (then a peninsula), but according to Ahlmann these islands were an independent centre of local glaciation, as the British Isles had been during the preceding period, and the local ice met the main ice-sheet in the fiords. On the coast of Nordland sufficient land lay bare to harbour a small Arctic flora, and Vaero, the southernmost island of Lofoten, had only small hanging snow-banks.

The interpretation of the British glacial deposits is still very much under discussion, but it seems probable that the Scottish highlands formed a subsidiary centre which glaciated the whole of Scotland and north-east England, sending a stream south-eastward, which was prevented from spreading across the North Sea plain by the presence of Scandinavian ice to the east and impinged

on the coast of Yorkshire and Lincolnshire, just reaching the northern extremity of Norfolk. Many British geologists regard this development as the concluding phase of a single glaciation of Britain, but the differences in the amount of weathering undergone are against such an interpretation. At the same time there were local glaciers in Cumberland, Wales and Ireland.

In England limits of this glaciation are characterized by a well-marked series of end-moraines, which indicate that the ice carried much surface detritus, and probably ended in a steep cliff. In Scandinavia, on the other hand, the centre of glaciation again lay over the low ground well to the east of the mountains, and the ice which reached Germany and Denmark was still largely free of surface detritus, and so did not form marked end-moraines. There was a difference, however. On this occasion, owing to the local nature of the elevation in Scandinavia, the ice-sheet did not extend its borders so far to the eastward, and the glaciation of Asia, as described in Chapter VII, was slight. Europe came more under the influence of cold north-easterly and northerly winds, and life on the ice-borders was not so easy as during the preceding glaciation. Man could still live near the ice, but he took to making his home in caves, and to clothing himself in skins for warmth.

After the ice had reached its Rissian maximum of glaciation the climate improved somewhat. The ice-edge retreated, leaving Denmark and the German coast, and vacating the Baltic basin, but not disappearing altogether from Scandinavia. At Rixdorf, near Berlin, there is a bed of gravel deposited in this "interglacial," containing numerous and well-preserved bones of the mammoth, woolly rhinoceros, aurochs, bison, horse, reindeer, red deer and other species of *Cervus*, musk ox and wolf—a cold temperate to sub-arctic fauna. In south Germany fresh water mollusca indicate that the summers in that district were almost as warm as at present, but the winters were probably severe. As

described in the preceding chapter this "interglacial" was the time of loess formation *par excellence*, with a continental climate and steppe conditions over much of central Europe.

Investigations at Skærumhede in Denmark show that this recession of the ice was accompanied by, and presumably due to, a fall in the level of the land relatively to that of the sea, for at the beginning of the oscillation the land lay about 350 feet above its present level, sinking gradually to only 30 feet above present. Even at its best during this interglacial the climate was almost sub-arctic in Denmark. In northern Finland, on the eastern edge of the ice-sheet, there was also an "interglacial," with a slight improvement in the climate accompanying a temporary submergence. But in Scandinavia there are no traces of any interglacial deposits of this period, and considering the cold climates which prevailed in Denmark and North Germany, it seems probable that Scandinavia continued to be glaciated during the whole period.

The mode of life among Mousterian men, who lived during this "interglacial," also points to a severe climate. For at this time man did not live in the open, but in caves and rock-shelters, and the practice of wearing the fur skins of animals as a protection against the cold, begun in the preceding Rissian glacial period, was not discontinued.

After the temporary subsidence had ceased, elevation again set in, causing a readvance of the ice-sheets and glaciers. The limits fell short of those of the preceding maximum, and the climate was not so severe, but in its general character it resembled that of the preceding maximum, but was much stormier, and there were probably frequent blizzards of the Antarctic type, carrying drift-snow. The new ice-sheet carried more surface detritus than its predecessors, presumably because all the high ground was not covered, and it formed high terminal moraines. The close association of cold ice

and irregular masses of bare sand and stones, strongly heated by the summer sun, set up a belt of powerful conviction very favourable for the development of blizzards; possibly there was something in the nature of an ice-cliff down which the cold winds could blow with great strength. At any rate, man found the near neighbourhood of the ice unpleasant, and went, so that there are no contemporaneous human implements near the moraines. The limits of the Scandinavian ice-sheet ran from the Norwegian coast across Denmark from north to south, through North Germany and northern Russia, and included Finland. The ice probably did not extend far across the North Sea plain, and in the British Isles there was no ice-sheet, but the high mountains of Scotland, Ireland, Wales and Cumberland bore small local glaciers, which were long enough to reach the sea in the Scottish highlands. The Alps bore considerable glaciers, indicating a depression of the snow-line of about 3500 feet, corresponding to a temperature 11° F. lower than the present.

After this ice-development had reached its maximum limits and remained there for perhaps a thousand years, retreat set in, and the Scandinavian ice once more withdrew from Germany and Denmark to the Baltic basin. But its edge was never far from the German coast, and occasionally readvanced across it, for numerous fossiliferous deposits are intercalated in boulder clay. The fauna and flora, which are well known, point to an arctic climate. At its best the mean temperature of July rose to about 50° F., and there was a vegetation period of three or four months with an average temperature of about 40° F., but these relatively mild conditions lasted at most for a few decades or perhaps a century at a time, and the winters were severe throughout. The duration of the whole of this "Baltic Interstadial" was from one to two thousand years.

Next followed the final readvance of the ice forming the great "Baltic" moraines which fringe the Baltic

coast of Germany, turning northward in the west into Denmark and in the east into Finland. There was a corresponding redevelopment of glaciers in the Alps (Bühl stage) and in the mountains of Ireland and Scotland, though these probably failed to reach the sea even in Scotland. This period gave us a repetition of the climate of the preceding maxima. In this case we have definite evidence of the presence of a belt of easterly winds on the southern side of the ice-sheet, in a series of "barkans" or fossil dunes in Holland, Germany and Galicia. These dunes were formed of fine ice-deposited material, and they are crescent-shaped, with their convexities to the east, indicating that they were built by strong easterly winds. A moment's consideration will show the truth of the latter statement. Suppose there is an isolated round hillock of sand exposed to strong easterly winds. The sand grains will travel up the easterly windward slope of the hillock and roll down the westerly leeward side. In this way the whole hillock will advance very slowly westwards. But in the centre, where the hillock reaches its greatest height, the grains will take longer to reach the highest point than near the edges, where they have not to rise so high. At the edges a strong gust will carry some of the heavier grains right over the dune, while nearer the centre they will be left half-way, and when the gust ceases will perhaps roll back to their original position. In this way the margins of the dune will advance westward more rapidly than the centre, producing the crescent shape with the convex side to the east. At the time of their formation these dunes must have had their steepest side to the westward, but the westerly winds which have prevailed during the last few thousand years have succeeded in modifying that detail, without destroying the general shape of the dunes, and the steepest slopes are now on the eastern side. The preservation of the original shape, in spite of the subsequent development of westerly winds, is due in

part to the coating of vegetation, which protected the dunes as soon as more favourable conditions occurred, and probably in part to the lesser velocity of the westerlies. If the period of east winds and dune formation had been long enough, we might have had another deposit of loess, but it was short, and vegetation, which is necessary to the genesis of true loess, had no time to establish itself before the climate changed again with the final retreat of the ice. The climate of this period in Rumania has been ably described by G. Murgoci: "In general the prevailing climate of the time of the formation of loessoid soils and blown sands must have been that which is named by E. de Martonne the aralian climate, a dry climate with some rain in spring to call forth a poor and transient vegetation and to maintain the flowing water in rivers and lakes. The temperature with great extremes, in summer up to 120° F. and in winter below 20° F., was the characteristic of this climate; the atmosphere was very dry in the hot season, but in the rest of the year there was some humidity in the air and moisture in the soil, the water of the subsoil being not very deep. The atmospheric precipitation in this region was caused by the south-west wind just as at present; but the dominant wind giving the character of a dry continental climate was the north-east wind (Crivat) which has left its traces in the fossil dunes of the Baragan."

A history of the changes of climate in Europe which followed the maximum of the last readvance of the ice-sheet must be left to later chapters.

BIBLIOGRAPHY

Brooks, C. E. P. "The correlation of the Quaternary deposits of the British Isles with those of the continent of Europe." *Ann. Rep. Smithsonian Inst.*, 1917, pp. 277–375. [Full list of references.]

Penck, A., and Brückner, E. "Die Alpen in Eiszeitalter." 3 Vols. Leipzig, 1901–9.

Gagel, C. "Die Beweise für eine mehrfache Vereisung Norddeutschlands in diluvialer Zeit." *Geol. Rundschau*, 4, 1913, p. 39.
Wahnschaffe, F. "Die Oberflächengestaltung des norddeutschen Flachlandes." Stuttgart, 1910.
Svastos, R. "Le postglaciare dans l'Europe centrale du nord et orientale." *Ann. Sci. Univ. Jassy*, 4, 1908, p. 48.

CHAPTER VI

THE MEDITERRANEAN REGIONS DURING THE GLACIAL PERIOD

Our knowledge of the history of the Mediterranean basin during the Glacial period is not nearly so complete as is that of the more northern regions, chiefly for the reason that during most of the period the land lay above its present level, and except for local glaciers in the mountain regions there was no ice to leave us a record of the changing climates. Most of what we do know relates to the relatively brief periods of submergence.

At the beginning of the Glacial period the sea lay some 500 feet above its present level, and we can trace the first appearance of a northern marine fauna. This stage is known as the Calabrian; it is divided into two horizons—a lower, in which northern forms are still rare, and an upper, in which they are becoming abundant. The most typical species are two mollusca whose present habitat is the coast of Iceland—*Chlamys* (*Pecten*) *islandicus* and *Cyprina islandica*.

The Calabrian beach is not found on the coast of Spain or at Gibraltar, and in Algeria it probably occurs at a lower level. This suggests that the subsidence at this period was local, and the western lands stood up as a barrier against the Atlantic. There must have been a channel of some sort, however, on the site of the present Straits of Gibraltar, to provide an inlet for the immigrating northern mollusca. In the Maritime Alps,

and again in the eastern Mediterranean, the Calabrian beaches are at a much greater height owing to local elevation.

After the formation of the Calabrian beach the whole Mediterranean region was elevated above its present level. This elevation must be contemporaneous with the period of maximum elevation in north-west Europe associated with the great Mindelian glaciation. It is suggested that the "sill" of the outlet channel at Gibraltar was raised above the level of the Atlantic, and the Mediterranean became, first a closed salt lake, and then a pair of lakes, the eastern fresh draining into the western, which was salt, the two being separated by a ridge of land between Italy and Tunis. This period of elevation was long enough for a great deal of denudation to take place. Even in the Mediterranean this was a time of severe climate. On the eastern side of Gibraltar there are breccias, known as the "Older Limestone Agglomerate," which reach a thickness of 100 feet in places, and are now much weathered. Similar agglomerates are found in Malta. These resemble the "head" of the south of England, and appear to be due to frost action in a severe climate. In Corsica there are traces of four periods of mountain glaciation, and the two oldest of these are provisionally correlated with the Gunzian and Mindelian of the Alps. In the Balkan highlands there are traces of two distinct glaciations: the older, which was the more general and reached the greater intensity, probably corresponding to the Mindelian. In the Atlas Mountains there are great boulder moraines which seem to belong to three distinct glaciations, the oldest extending to about 2000 feet above sea-level, and the second terminating at about 4000 feet, while the third glaciation consisted of small valley glaciers only.

Towards the close of the Mindelian glacial period the land sank or the ocean rose again, and the waters of the Atlantic poured in, bringing with them a great number

of high northern and Arctic mollusca. The theory has been put forward that this influx was in the nature of a debacle and carved out a deep gorge through the present Straits of Gibraltar. The beaches deposited by this sea lie at a height of 250 to 330 feet above the present sea-level. The fauna resembles that inhabiting the northernmost parts of Europe at the present day, and the waters must have been several degrees colder than at present. This stage is termed the Sicilian.

As the climate improved the land gradually rose again, and the next general raised beach lies at a height of only about 100 feet in southern Italy (except where it has been elevated by local earth movements). Further west it lies still nearer the present sea-level—twenty feet in the Balearic Islands and only seven feet on the coast of Spain. On the coast of Algeria and Tunis this beach is found at a height of about forty-five feet.

The beach contains no trace of the northern fauna found in the Sicilian stage; instead it is marked by an assemblage of mollusca of a sub-tropical aspect, including *Strombus bubonius*, *Mytilus senegalensis* and *Cardita senegalensis*. The bones of large mammals are also found, including the hippopotamus and southern forms of elephant (*E. antiquus*) and rhinoceros (*Rh. merckii*). This warm stage corresponds to the Chellean interglacial fauna of northern Europe, though so far as I am aware no Chellean implements have been found associated with it.

About this time the Older Limestone Agglomerate of Gibraltar had been worn into caves, in which are found the bones of ibex, wild boar, leopard, spotted hyena, *Rhinocerus leptorhinus*, *Elephas meridionalis*, lion, southern lynx, bear, wolf, stag, horse, etc., so that the rock must have been covered by a rich vegetation, and must have had a greater extent than now, and a connexion with the continent of Africa. This is said to have been followed by a submergence of about 700 feet with numerous oscillations. This submergence, if it is really

attributable to the interglacial, must have been extremely local, and possibly it is much older.

After the warm Chellean period the Mediterranean region rose again, probably contemporaneously with the rise which caused the Rissian glaciation of northern Europe. But the climate was nothing like so severe as in the Sicilian. We have no old beaches containing a molluscan fauna of this period, but at the Grotte au Prince near Mentone, investigated by M. Boule, the *Strombus* beach is overlain by a bed of cemented pebbles and "hearths" containing Mousterian implements and bones of a temperate fauna. The Newer Limestone Agglomerate on the east of Gibraltar may have been formed during this period. The Mediterranean lands remained above their present level until the close of the Glacial period.

Each glaciation of northern Europe must have been a time of greater rainfall as well as of lower temperature in the Mediterranean. The glacial anticyclone in the north displaced the storms from the Atlantic, which now mostly either skirt the north-west coast of Norway or pass across Denmark into the Baltic. These storms had to take a more southerly course, and entered the Mediterranean basin either across the south of France or in the neighbourhood of Gibraltar: tracks which are still occasionally followed in winter. These storms brought a rainfall much heavier than the present, and of a different character. The Mediterranean is now a "winter rain region," and the north of Africa is entirely rainless for several months in the summer. But during the "Pluvial periods" it is probable that rain fell throughout the year, though the winter still had more than the summer. The winter rains were in the form of steady falls of long duration, such as we experience now in England, while the summer rains fell in short, heavy showers, perhaps accompanied by thunder. The Older Pluvial period, which corresponds to the Mindelian glaciation, had these conditions in their greatest develop-

ment. Depressions cannot live long without a supply of moisture, either from the sea or from transpiring vegetation, and at present such winter storms as enter the Mediterranean are almost confined to its surface, and on the African side rarely penetrate more than one hundred miles inland. But at the period of greatest elevation the shrunken Mediterranean offered no such great attraction, and with a comparatively well-watered Sahara the storms were able to pass much further south. Consequently, northern Africa possessed a number of large and permanent rivers which reached the sea. It was along these rivers and their banks that the fauna still inhabiting the Saharan oases made its way, to be isolated there by the decrease of the rainfall, so that crocodiles and many species of fish now live in isolated pools and in rivers which lose themselves in the sand.

In Egypt and Syria the first Pluvial period is double, corresponding to the Gunz and Mindel glaciations, with an intervening phase of feeble desert conditions, during which, however, the rainfall remained greater than the present. The second stage, corresponding to the Mindelian, indicates very great activity; at this time the Jordan Sea (Dead Sea) reached its greatest area, extending to the northern end of the Sea of Tiberias.

Conditions in Egypt at this time are very interesting. South of Cairo the alluvial Nile muds are at most thirty to thirty-five feet thick, and ten feet of this thickness has been deposited since the time of Ramesis II. If the rate of deposition has been uniform, this gives a period of only 14,000 years for the deposition of the whole thickness of the muds. The theory put forward by Hume and Craig (British Association Report, 1911, p. 382) is briefly as follows: The mud deposits of the Nile valley are carried down with the flood waters of the Blue Nile, Atbara, etc. These rivers rise in the highlands of Abyssinia, where they are fed by the rains

of the south-west monsoon. The incidence of the monsoon is determined by a number of factors, prominent among which is the temperature of southern Asia. During the winter, at present, the low temperature of the Himalayan and Tibetan region results in a great outflow of cold air, which strikes the coast of Africa as the cool dry north-east monsoon. During this time there is very little rain in Abyssinia. It is only when the Asiatic land-mass warms up in summer that the south-west monsoon is established.

But during the Glacial period, as we shall see, there was a great development of snow and ice on the Himalayas. The result was that winter conditions, i.e. the north-east monsoon, prevailed more or less throughout the year, and the rivers which feed the Nile contained only a small volume of water. Hence they lost themselves in the desert before reaching Cairo, and the Nile in its present form did not exist. On the other hand, the westerly winds which at present bring a moderate winter rainfall to the coast of Syria were greatly increased in intensity and extended further south, replacing the dry north and south winds now occupying the Nile valley. The northerly winds prevailing in the Nile valley in summer are associated with the low pressure area over the neighbourhood of the Persian Gulf, which in turn is due to the extremely high temperature experienced there. Even at the present day the highest hills of Sinai penetrate above the north winds into a westerly current, and a moderate fall of temperature over the Persian Gulf would inhibit the north winds in the Nile valley altogether and allow the westerly winds to reach the surface. These strong westerly winds brought a heavy rainfall to the hills, now almost rainless, between the Nile and the Red Sea. Powerful streams descended the western slopes of these hills, bringing great quantities of debris, which formed delta-terraces forty or fifty feet thick where the streams debouched on to the Egyptian plain. These are especially well developed at Oina,

the meeting place of several dry valleys from the hills, and it is remarkable that they actually cross the present site of the Nile valley and reach the desert on its western side, additional evidence that the Nile was not then in existence.

These gravel terraces contain numerous stone implements of early (pre-Chellean) types, showing that at this time Egypt had sufficient rainfall of its own to support human life.

The moist westerly winds carried the climate of the Mediterranean coast far into the desert. For instance, in the oasis of Khargeh, in latitude 25°, grew the evergreen oak and other plants not now found south of Corsica and southern France.

The Mindelian Pluvial period was followed by a long dry period corresponding to the Chellean, when desert conditions supervened. The Nile as we know it first appeared during this period. Terraces were formed on the sides of the valley, probably during the submergence which produced the *Strombus* beaches of the western Mediterranean; these contain Chellean implements. During the succeeding elevation the Nile cut its bed below the present level.

The Rissian glaciation of northern Europe is represented in Egypt by a second rainy period, the Lesser Pluvial period. Rain again fell on the Red Sea hills, forming a newer set of gravel terraces, but these are much smaller than the great Mindelian terraces. No terraces are known representing the Wurmian period, and the country does not seem to have been inhabited at this time. Probably the climate was semi-desert, with not enough rainfall of its own to support human life, and yet without the fertilizing Nile floods to enable human life to exist without rainfall. As has been said, the present regime did not begin until the last glaciation was nearly over, about 12,000 B.C.

BIBLIOGRAPHY

Gignoux, M. "Les formations marines pliocènes et quaternaires de l'Italie du Sud et de la Sicilie." *Ann. l'Univ. Lyon*, n.s., Vol. 1, fasc. 36, Paris, 1911, pp. 693.

Depéret, C. "Les anciennes lignes de rivage de la côte française de la Mediterranée." *Bull. Soc. Geol. de France*, ser. 4, Vol. 6, pp. 207–30.

Douvillé, R. "Espagne," *Handbuch regional Geol., H.* 7, 1911. (Includes Gibraltar and Balearic Is.)

Hume, W. F., and Craig, J. I. "The Glacial period and climatic change in North-east Africa." *Rep. Brit. Assoc.*, 1911, p. 382.

CHAPTER VII

ASIA DURING THE GLACIAL PERIOD

The great area of Asia is at present but little explored for glacial traces, but a certain amount of evidence has been collected, and the data from the various mountain districts are consistent enough to map out the general trend of the history of the continent during the Ice Age.

The earth-movements which brought about the present configuration of Asia were completed as regards their major details by the close of the Tertiary period. These movements left a number of great basins closed in on all sides by enormous mountain walls; at first all these basins contained lakes, and the subsequent geographical history has consisted largely in the gradual silting up of the lakes and the development of more and more arid conditions. The fluctuations of the Ice Age were superposed on this secular desiccation, but except in northern Siberia the part played by glaciation in the history of the country has been relatively small.

Consider for a moment the relief of Asia. The orographic centre may be taken as the great Pamir plateau, the "Roof of the World," with an average elevation exceeding the height of Mont Blanc, diversified by ranges of mountains exceeding 25,000 feet in places. East of this is the great plateau of Tibet, 10,000 to 17,000 feet, bounded on the south by the mighty Himalayas, and on the north by the mountains of Kuen Lun. On the north the Pamir plateau is bounded by the Alai range, passing north-east into the Tian-Shan mountains, rising to 24,000 feet in Khan-tengri. Still

further north-east comes the Altai range, with an elevation of 9000 feet. East of Lake Baikal lie a series of ranges averaging 8000 feet in height, and passing into the Stanovoi range of eastern Siberia and the mountains of Kamchatka.

The Himalayas, owing to their heavy snowfall derived from the south-west monsoon, bear numerous great glaciers, but with the series of ranges extending from the Pamirs to north-east Siberia the case is different. These ranges all rise above the snow-line in places, but owing to the scanty snowfall they bear at most a few small glaciers on their northern sides, and none at all on the slopes which face towards the deserts of western China, and in all cases the glaciation is very slight in comparison with their elevation.

This distribution was characteristic also of the Ice Age. In the Pamirs there is evidence of two periods when the glaciers had a greater extent ; in the first they extended to a level of 5000 feet, in the second to 7000 feet. The present limit of the glaciers lies at about 10,000 feet. The first glaciation was remote, for the moraines are worn and weathered, but the second was much more recent, for the moraines are fresh, and in some cases there are still masses of "dead" ice buried beneath great accumulations of debris and occasionally exposed by slips.

In the Tian-Shan mountains there are remains of two glaciations. The earlier was the greater, and the glaciers descended well below 10,000 feet. This glaciation was followed by a long interval, when the erosion of the rivers converted the U-shaped glacial valleys into V-shaped gorges. A second glaciation descended to a level of 10,000 feet, and again developed U-valleys to this level ; the end moraines of these glaciers are young and fresh-looking. In the Altai range there were also two glacial periods. In the older and greater the snow-line was depressed by 3000 feet. The glaciers attained a length of twelve miles and descended to a level of

only 3000 feet above the sea. The second glaciation was less extensive.

So far we have been dealing with small mountain glaciers only. But in north-eastern Siberia we find a different state of affairs. The Stanovoi and Verkhoiansk mountains were heavily glaciated, and during the first glaciation were probably the centre of an actual ice-sheet similar to that of Scandinavia. The ice descended the valleys of the rivers Yana, Indijirka and Kolyma and covered the New Siberian Islands, which were at that time connected with the mainland. The upper valley of the Lena was also heavily glaciated by an ice-sheet moving southward, probably from the Patom highlands. When this glaciation drew to a close the source of supply among the mountains ceased, and the ice on the lowlands and in the lower parts of the river valleys was left stranded as "dead" ice. When the mountains became free of ice, the re-born rivers carried great quantities of moraine clay and other debris with them, and flooding the ice-surface over wide areas deposited their load above the ice. In course of time the remains of the ice-sheet were deeply covered by a layer of earth and stones, which prevented the ice from melting and preserved it to the present day. This is the probable origin of the well-known "fossil ice" of Siberia. Other theories have been put forward, such as the freezing of ground water during the winter, but none are satisfactory, and that given here was generally adopted by Russian geologists.

During the long warm interglacial which followed, the surface of the thick earth-layer covering the ice bore low-growing herbage in the same way as any other earth-surface. (A parallel to this is found in Alaska, where the glaciers terminate among the forests, which actually grow over the moraines covering their snouts.) The rivers cut their way down through the earth and ice, exposing ice-cliffs, which were quickly buried by talus from above. The mammoth and woolly rhinoceros

roamed the land, and their tusks remain in great numbers as the "fossil ivory" of Siberia and the Arctic Ocean. Still more remarkable is the fact that mammoths have been found buried entire, and preserved by the frozen ground to the present day. It is difficult to say how the animals reached such a position, but most probably they sank into swamps formed during the summer and were quickly frozen.

In western Europe the mammoth and woolly rhinoceros are regarded as indications of severe climate, but their presence in north-eastern Siberia in large numbers is evidence of a climate probably somewhat warmer than that of the present day, especially as regards the length of the vegetation period. Probably the winter snowfall also was less than now. It is difficult to see how the fauna could have moved from, say, the New Siberian islands into a warmer climate each winter, for the winter climate becomes markedly more severe as one penetrates south from the Arctic coast into the interior. It is possible that the mammoth and woolly rhinoceros hibernated during the winter.

After this interglacial there came a recrudescence of glacial conditions. In this case, however, the Stanovoi and Verkhoiansk mountains and the Patom highlands were not buried in an ice-sheet, but became the centre of great valley glaciers, which reproduced the well-known glacial phenomena—corries, glacial terraces, U-valleys, etc. The ice extended down the great river valleys, leaving a typical moraine landscape on either side, and again reached the New Siberian islands. In course of time the climate ameliorated, again commencing in the south, and again the ice of the glaciers was buried. In the New Siberian islands the happenings are summarized very expressively by a rock-section described by Vollossovitsch. The bottom of the section is formed by the older layer of "fossil ice." Above this is a sandy clay with remains of meadow vegetation and shrubs, followed by a fine clay with remains of alder and white

birch, and the bones of mammoth and rhinoceros. Above this comes another layer of " fossil ice," followed by clay with the dwarf birch, Arctic willow, and bones of musk ox, horse and later mammoth. After this the coastal regions sank beneath the sea for a time and marine clays were formed in a climate somewhat warmer than the present. When the land rose again the conditions resembled those now prevailing.

Though not part of Asia, reference may be made here to the glaciation of Spitzbergen, which runs strictly parallel with that of northern Siberia. The first glaciation was of the " ice-sheet " type, originating in the region north of Storfjiord, filling the whole of that fiord and extending south of South Cape. Barentz Land and Stans Foreland were at least partially ice-covered. The ice-floor of Spitzbergen, which resembles that of Siberia, may have originated during this glaciation. This was followed by subsidence to 230 feet below present level, and the ice retreated, giving place to an " interglacial," during which frost was very active and largely obliterated the traces of the ice-sheet. This " interglacial " was followed by a second extension of the ice, which affected the valleys and fiords only, leaving the plateaux free. This again was followed by subsidence and a warm period.

In southern Kamchatka there was a great development of ice, but in the form of a network of glaciers rather than of an inland ice-sheet. In the east the ice reached the sea, but on the west it left a zone forty to sixty miles broad, and up to a thousand feet high unglaciated, so that there was the same difference then as now between the rainy east side and the drier west side of the peninsula. The present snow-line in the centre of southern Kamchatka is about 5500 feet, and at the maximum of the glaciation it must have been fully 3000 feet lower.

This glaciation was followed after an interval by a second, which was confined to the mountains. The

moraines of this glaciation are much fresher than are those of the earlier one.

In Japan the mountains were only just high enough for glaciers to develop in the north. The moraines are old and weathered, and their meaning has been disputed; but recent work by Simotomai and Oseki seems to have established their glacial origin. The depression of the snow-line necessary to produce them—about 3000 feet—fits in very well with that observed in adjoining parts of the continent. The phenomena were confined to small hanging glaciers in the Hida mountains which cut out corries and descended to a level of about 8000 feet, leaving small morainic ridges. This glaciation was probably contemporaneous with the earlier and greater glaciation of Siberia. To the succeeding interglacial may be attributed the marine deposits found near Tokio containing corals, at present living some distance further south. No trace of any subsequent glaciation of Japan has yet been found.

J. S. Lee has recently called attention to the existence of a glaciated area in northern China, the evidence for which consists of moraines and striated slabs found in southern Chi-li, and a glaciated valley with travelled boulders in the north of Shan-si. The glacial deposits in Chi-li are closely associated with a layer of quartzite pebbles which continues southward beneath the loess on the eastern side of the Tai-hang range, and is attributed to either torrential rain or the melting of glaciers. J. Geikie had long ago stated that there once existed ice-masses all over northern China, and considered that the ice came from the Himalayas. This origin is impossible, the probable source of the ice being the Yablonoi mountains in southern Mongolia.

In the Himalayas the glaciers formerly had a much greater extension. The glaciers at present extend downwards to 11–13,000 feet, but old moraines are found at 7000 feet, and near Dalhousie on the southern slopes of the Dholadar range to 4740 feet.

On the northern side of the Himalayas there was a great development of ice over Tibet, but there was not a real ice-sheet such as occurred further north. Oldham records three separate periods of glaciation in Kashmir, but it is not possible to discuss the glacial history of the Himalayas in detail. The latter is likely to prove complicated, since the range is still rising, and has probably been doing so either continually or intermittently throughout the Quaternary.

The great development of ice in Tibet, which is now semi-arid, owing to interception of the rain-bearing winds by the Himalayan range, suggests a considerable alteration in the present meteorological conditions. The Tibetan snowfall was probably due to the Mediterranean storms, which now give a small winter rainfall in north-west India, and which during the Glacial period greatly increased in strength and frequency and occurred throughout the year (Chapters IV and VI), giving the Pluvial period of North Africa. These storms would pass across Persia and continue to the north of the Himalayas, probably breaking up over the Tibetan plateau.

It is evident that, taking northern Asia as a whole, there have been two general glaciations, of which the first was the more severe, separated by a long interglacial, during which, in Japan at least, the climate became appreciably warmer than the present. The first glaciation is related to elevation in the Arctic basin, which closed Bering Strait and united the New Siberian islands to the mainland. It was almost certainly contemporaneous with the first glaciation (Gunz-Mindel) of Europe. The ice began as glaciers on the mountains as in Scandinavia, but, owing to the scanty supply of snow, developed more slowly and only reached the dignity of ice-sheets in north-east Siberia. Then followed subsidence below the present level, wider opening of the Bering Strait, warm ocean currents and a long interglacial. After this there was

again elevation and a re-development of ice-sheets, but apparently once only, and not twice as in Europe. This glaciation probably corresponded in point of time more or less with the Rissian, for the post-glacial dry of central Asia appears to have been of enormous period length.

There is one other phenomenon which must be considered in connexion with the glacial history of Asia, and that is the loess. Loess has already been referred to in connexion with the glaciation of Europe, but in China its development is much greater. Richthofen, who first studied this deposit attentively, and to whom we owe the æolian theory of its origin, found that it was formerly deposited in China over a much greater area than that over which it is accumulating at present, and attributes this cessation of growth to the heavier rainfall brought by the Glacial period, which enabled the rivers to cut back their valleys and drain some of the mountain basins, formerly enclosed. He considered that loess can accumulate more rapidly in a closed basin, where occasional floods leave behind them layers of bare sand and mud, easily dried to dust, than in a well-drained river valley where floods are rare.

In western Asia outside the limits of glaciation we have further evidence of at least one Pluvial period in the former far greater extent of all the enclosed lakes, due partly to greater precipitation and partly to decreased evaporation. The Caspian Sea and Aral Sea were extended to several times their present size and united into a single sheet of inland water. Lake Lop-nor was greatly increased in size, and many of the desert basins, at present dry, were the sites of salt lakes. This is especially the case in central Persia, where there were large salt or brackish lakes.

These Pluvial conditions have not yet been correlated with the glaciations of Asia, but, by analogy with the conditions in America discussed in the next chapter, there is little doubt that they were contemporaneous

with one at least of the glaciations, and probably there were two main Pluvial periods coinciding with the two Glacial periods. At Baku, on the shores of the Caspian river, Pumpelly has found old shore lines at heights of 600, 500, and 300 feet above the present level of the water. Still more interesting are the conditions found by Sven Hedin in the Kavir basin of Persia. Here there are lacustrine clays and silts referable to a Pluvial period covered by beds of almost pure salt, suggesting a rapid and complete drying up of the lake. Above this again are further silts indicating a return of Pluvial conditions. In addition to this the succession of silts and clays show that there were several minor fluctuations superposed on the main wet periods, giving ten moist phases altogether.

BIBLIOGRAPHY

Many of the more important references are in Russian, and for these reference is made to summaries in other languages.

Sevastianov, D. P. "On the glaciation of the extreme north-east of Siberia." *J. 12 Congr. Russ. Nat.*, Moscow, 1910, No. 10, p. 491. (Russian, see *Geol. Centralblatt*, 15, p. 205.)

Riesnitschanko, W. "Ancient and modern glaciers of the south-western Altai." *Mem. Russ. Geogr. Soc.*, 48, 1912, p. 357. (Russian, see *Geol. Centralblatt*, 19, p. 131.)

Komarov, W. "On the Quaternary glaciation of Kamchatka—Travels in Kamchatka in 1908–9," Vol. 1 (Russian, see *N. J. Min.*, 1915, Pt. 2, p. 117).

Merzbacher, G. "Zur Eiszeitfrage in der nordwestlichen Mongolei." *Peterm. Mitt.*, Gotha, 57, 1911, p. 18.

Prinz, Gyula. "Die Vergletscherung des nördlichen Teiles des zentralen Tien-schan-Gebirges." Wien, *Mitt. K. K. geogr. Gesellsch*, 52, 1909, p. 10.

Obrutschev, W. A. "Geological map of Lena gold-bearing region." St. Petersburg, 1907. [Text in Russian; see *Geol. Centralblatt*, 12, pp. 507–9.]

Simotomai, H. "Die diluviale Eiszeit in Japan." Berlin, *Zs. Ges. Erdkunde*, 1914, p. 56.

Oseki, K. "Some notes on the glacial phenomena in the North Japanese Alps." Edinburgh, *Scot. Geogr. Mag.*, 31, 1915, p. 113.

Lee, J. S. "Note on traces of recent ice-action in North China." *Geol. Mag.*, 59, 1922, p. 14.

Burrard, S. G., and Hayden, H. H. "A sketch of the geography and geology of the Himalaya Mountains and Tibet." Calcutta, 1907–8.

Hogböm, G. "Bidrag till Isfjordsomradets kvartargeologi." *Geol. Foren. Stockholm Forb.*, 1911. (Spitzbergen; résumé in German.)
Richthofen, F. Freih. von. "China." 5 Vols., 1907–12. (Loess, see Vol. 1, p. 74 ff.)
Hedin, Sven. "Some physico-geographical indications of post-Pluvial climatic changes in Persia." *Internat. Geol. Congr.*, Stockholm, 1911. "*Die Veränderung des Klimas.*"

CHAPTER VIII

THE GLACIAL HISTORY OF NORTH AMERICA

THE glaciation of North America was even greater and more complicated than was that of Europe. It spread from three main centres, the Cordilleran or Rocky Mountain centre, the Keewatin centre west of Hudson Bay, and the Labradorean centre. Vancouver Island in the west and New Brunswick and Newfoundland in the east, were also independent centres of glaciation, and ice from the latter may have reached the coast of the United States in places. The ice covered an area of about 4,000,000 square miles, and the main ice-sheet extended to 38° N., or twelve degrees further south than the Scandinavian ice-sheet. Nine stages are recognized by American geologists, though opinion is divided as to whether all the stages of "deglaciation" represent real interglacial periods. The sequence is as follows:

1. Nebraskan, Jerseyan or pre-Kansan glaciation.
2. Aftonian deglaciation.
3. Kansan glaciation.
4. Yarmouth deglaciation.
5. Illinoian glaciation.
6. Sangamon deglaciation.
7. Iowan glaciation.
8. Peorian deglaciation.
9. Wisconsin glaciation.

On the other hand, in the northern part of the Rocky Mountains there is evidence of only two Glacial periods, separated by a single long interglacial, though perhaps

the second glaciation was double. Further south, out of reach of the main ice-sheets, there are traces of two and in places three separate developments of valley glaciers resembling those of the Alps.

As in the case of Europe, the literature of the subject is extensive and conflicting, but the following summary of the course of events represents the views of most moderate American geologists.

The Quaternary period opened with extensive elevation of the whole North American continent, which raised the Rocky Mountains several thousand feet above their present level and extended the continental area over much of the northern archipelago. In the east Newfoundland is considered to have been raised at least 1000 feet, a movement which converted the banks into dry land and interposed a large cold area in the path of the moisture-bearing southerly winds. As in northern Europe the high mountains of the west were the first to develop large glaciers, which coalesced into an ice-sheet, filling the valleys and rising up the slopes of the mountains until it reached a thickness of 5000 feet. In Puget Sound the ice was 4000 feet thick, but seawards the slope is very rapid and the ice was unable to extend far from the shore. This ice-sheet extended south-eastwards some distance into the United States, forming the first ground moraine of that district. Probably while this Cordilleran glaciation was still in progress ice began to spread outwards also from the Labradorean centre, forming the oldest drift of that region. These oldest deposits are, however, not yet well understood.

This oldest boulder-clay is separated from the moraines of the main glaciation near its southern limit by river gravels containing the remains of mollusca and large herbivorous mammals—extinct species of horse, the hairy mammoth of the old world (*Elephas primigenius*), and two other extinct species of elephant, and also the true American mammoth. This is the Aftonian fauna

which has been claimed as evidence of an Interglacial period. That it evidences a retreat of the ice-edge in that particular region is certain, but that the climate became really temperate is very doubtful. More probably it corresponds to the Gunz-Mindel "interglacial" of the Alps, and was formed when the Cordilleran ice-sheet was retreating, but before the Keewatin sheet had reached its maximum.

The Aftonian stage was followed by the Kansan glaciation, when the ice-sheets reached their maximum area over the greater part of North America. The chief centre of glaciation at this stage was the Keewatin, west of Hudson Bay. While it is certain that the Keewatin centre reached its maximum later than the Cordilleran, geological opinion in America is divided as to whether or no the two ice-sheets ever coalesced, but it is difficult to understand how an independent ice-sheet could have grown up on the comparatively low ground of the Keewatin centre. Most probably the course of events here was an exact parallel of that in the better-known Scandinavian region—the Cordilleran ice-sheet extended eastwards over the lower ground until a glacial anticyclone developed east of the Rockies. When this happened the supply of moisture to the western part of the ice-sheet fell off somewhat, and the eastern part took on an independent life, ultimately becoming the main centre of glaciation. It was while these changes were in progress that the southern limit of the ice retreated northwards and the "Aftonian" deposits were formed.

The next stage (Kansan) occurred when the ice from the Keewatin centre spread outwards in all directions, and in the south reached the maximum limits of glaciation in America. In the west this sheet overlapped on to the ground-moraine of the former Cordilleran ice, but the Rocky Mountains were too far away and too high for Keewatin ice to dominate them and overflow them from east to west. Instead these mountains must

have maintained an extensive glaciation of their own.

With the growth of the Keewatin centre the Labradorean also decreased, but more slowly, and this change was not associated with a retreat of the southern ice-edge, so that there was no corresponding " interglacial " in the east of the United States. The moraines of these older glaciations resemble those of the early ice-sheets of Europe in presenting only featureless level surfaces of boulder-clay without morainic ridges, lakes and the other characteristics of ice-bearing surface detritus, and there is no doubt that conditions at the southern edge were similar—the climate was severe in winter, but not insupportable in summer. At the same time it was decidedly more severe than the present, even as far south as Florida, where there are colonies of northern plants, which migrated southwards during the Ice Age, still living on local cold slopes with a northerly aspect. After the maximum of glaciation the disappearance of the ice took place gradually and chiefly by ablation, for there are none of the extensive river gravels and flood terraces which we should find had the melting been rapid. It is only in the valleys of the Rocky Mountains that such deposits occur, testifying to conditions such as obtained in the Alps.

The succeeding Yarmouth stage of deglaciation was very long, corresponding in this respect to the Mindel-Riss interglacial of Europe. The Kansan moraine was weathered to a depth of ten or twenty feet, and four-fifths of its surface was removed by the erosion of streams and rivers. In the mountain districts the side streams which had been left occupying " hanging valleys " by the over-deepening of the heavily glaciated main valleys, had time to cut out uniformly graded broad V-shaped valleys descending to the level of the main stream. In the Great Basin also, where the periods of high water-level are considered to correspond to the main glaciations, the interval of low water

corresponding to the Yarmouth stage was very long. A rough estimate of its length is about 200,000 years —somewhat shorter than the Mindel-Riss. Actually, though the Kansan and Mindelian glaciations were approximately contemporaneous, the subsequent recurrence of glaciation in America appears to have preceded slightly that in Europe.

Of the climate of this stage we have unfortunately little evidence. Old land surfaces of this age are known, containing deposits of peat and bones of the wood rabbit and common skunk, but both of these animals have a wide range. Perhaps the climate resembled the present during most of the period; there is no evidence that it was ever warmer, and it appears quite likely that ice-sheets maintained their existence in the far north through the whole of this stage.

After this interglacial there set in a period of renewed elevation in the Rocky Mountains and in the Labrador-Newfoundland centres, which brought about a recurrence of the glaciation. In the Rocky Mountains the ice was not so thick as in the preceding stage, but all the valleys were occupied to a considerable depth and the ice spread out to the eastward. The Labrador ice-sheets also developed again, forming the Illinoian glaciation, the moraines of which are found as far west as Illinois, but no moraines are known of this age due to the Keewatin ice-sheet. The latter developed later, and is classed by some American geologists as a separate glaciation, the Iowan, which is only certainly found in northern Iowa, but may be represented further east by a thin sheet of boulder-clay overlapping the Illinoian moraine. The supposed interglacial between the Illinoian and Iowan, the "Sangamon Stage," is represented only by land surfaces formed of the Illinoian moraine and covered by the loess or locally by the equivalent of the Iowan moraine, and there is no evidence that the ice-edge retreated far. Other American geologists, including F. Leverett, do not recognize the existence of

a separate Iowan glaciation, and as the amount of weathering and denudation undergone by the two moraines differs very little, this seems the more natural view. The natural explanation seems to be that this was another case of "glacial piracy," the Keewatin ice-sheet, owing to its lesser snowfall, developing more gradually, and finally diverting the supply of moisture from the Labradorean ice-sheet, until it reached a maximum after the latter was already on the wane. Both these sheets of drift present similar flat features to the Kansan sheet, without morainic ridges.

Leverett's interpretation of the succession is as follows: The third (Illinoian-Iowan) glaciation was followed by a period of moist climate, when peat-bogs were formed on level poorly-drained surfaces, while elsewhere coniferous forests developed. This was followed by a period of dry steppe-like conditions with a cold temperate climate, when the great American loess sheet was deposited. This loess sheet extends northwards, overlapping the Iowan moraine, and in places passing under the Wisconsin drift. The material has come from the west, and probably most largely from the dry plains east of the Rocky Mountains, from which it diminishes in thickness eastwards. But unlike Europe this phase of steppe conditions was followed in America by a definite interglacial, when the climate seems to have become rather warmer than the present. In the northern States an old land-surface formed on the loess, and, termed the Peorian stage, is overlain by the Wisconsin drift; but near Toronto, on the shores of Lake Ontario and in the Don valley, the gap represented by this land-surface is partly filled by a remarkable series of lacustrine deposits known as the Toronto stage. The Lake Ontario beds indicate a climate slightly colder than the present, but the Don valley beds contain plants and animals living in the central States, and refer to conditions more favourable than those now found in the district.

The duration of this interglacial has been worked out

in a remarkable way by A. P. Coleman, who on the basis of wave-action estimated it as 62,000 years, which agrees very closely with the 60,000 years found by Penck and Brückner in the Alps. This period was not long enough for streams in the "hanging valleys" to cut out uniformly graded valleys down to the main rivers, and was consequently much shorter than the preceding interglacial.

The last glaciation of North America was the Wisconsin, which closely resembles the Wurmian of Europe both in its relations to the older glaciations and in the rough topography and unworn character of its moraines. It extended within the limits of the Kansan drift across fully two-thirds of the continent, from Nantucket and Cape Cod through Long Island, northern New Jersey, Pennsylvania, southern New York, Ohio, Indiana, Illinois, Michigan, Wisconsin, Minnesota, Iowa and the Dakotas, Manitoba, Saskatchewan and Alberta. At the same time the Cordilleran centre probably bore increased local valley glaciers.

Like the Wurm glaciation, the Wisconsin was double. The older moraines are well-marked, and in places are covered by a foot or two of loess, though this deposit reaches nothing like the thickness of that overlying the moraines of the earlier glaciations. The moraine under this loess is very little weathered, so that the time interval was very short; possibly this loess is redistributed older loess associated with glacial east winds. The ice of the first glaciation melted very slowly and there is very little gravel outwash to the moraines. But "after the Wisconsin ice-sheet had reached a position a little outside the limits of the Great Lakes the retreat became much more rapid, and large outwash aprons were formed from which valley trains of gravel led far down the drainage lines. From this position . . . the moraines are practically free from loess-like silts."[1]

From this point onwards the glacial history of America

[1] Leverett, F. (see Bibliography).

is one of irregular retreat, with occasional halts or even readvances resembling those of the Scandinavian ice. Banded clays are found similar to those used so successfully by Baron de Geer in dating the retreat stages of Scandinavia, and this geologist has recently been investigating them, but until his results are worked out no correlation with Europe can be attempted.

A natural clock of another type is provided by Niagara Falls, which are cutting their way back up the gorge at a rate which has been definitely ascertained. Taking into account the varying amounts of water which have passed over the falls at different stages of post-glacial geography, the duration since the region became free of ice has been calculated at about 20,000 years, which agrees closely with the time elapsed since the Scandinavian ice-sheet left the North German coast.

Before leaving North America it is necessary to give a brief account of the phenomena outside the main centres of glaciation, and especially of the history of the Great Basin between the Sierra Nevada and Wasatch Mountains. The lowest levels of this basin are at present occupied by several salt lakes without outflow, of which the largest is the Great Salt Lake, the level of the water being determined by the balance between inflow of the rivers and evaporation from the surface. Twice in the past this balance has been decidedly more favourable, and then the lakes grew to many times their present size. The two greatest of these old lakes have been fully described under the names of Lake Bonneville (of which the Great Salt Lake is a vestige) and Lake Lahontan, further to the west. The investigations have shown that before the Glacial period, and extending back into an unknown past, there was a period of great aridity. To this succeeded a long period of high water, during which, however, neither of the lakes overflowed. This stage was followed by a very long period of great aridity, during which the lakes dried up completely, and all their soluble matter was deposited and buried

by alluvial material. This period was followed by a return of moist conditions, during which the water reached a higher level than before, and in the case of Lake Bonneville actually overflowed into the Snake river, cutting a deep gorge. This period, however, was shorter than the preceding moist period. It was followed by an irregular fall interspersed with occasional slight rises, but ultimately both lakes descended below their present level and probably again dried up completely. Both lakes suggest that this low level was followed by a third rise to a height very slightly above the present level, followed by a slow fall in recent years.

The relations of the periods of high water to the glaciations are not clear in these large lakes, but in the Mono Basin, a small basin further west, there is no doubt that the two were almost contemporaneous, high water accompanying the maxima of glaciation and extending some way into the retreat phase. The very long interval between the first and second period of high water, several times that since the second period, agrees with this correlation. We find then that south-west of the main glaciated area there was a district of greater precipitation or less evaporation, or more probably both. This is confirmed by the valley moraines of all this region —Sierra Nevada, Uinta and Wasatch mountains, Medicine Bow Range of northern Colorado, etc., all of which indicate two glaciations, of which the first was the greater, separated by a very long interval. In several ranges the moraines of the second glaciation are double, and some geologists consider that there were three Glacial periods in these regions.

In the extremely arid region of Arizona, on the other hand, which is considerably further south, the evidence of the Gila conglomerates indicates that while frost was very active, the increase of precipitation, though undoubtedly present, was comparatively slight. This shows that the climatic balance was not greatly disturbed, the chief effect being an important lowering of tempera-

ture, probably due to cold northerly winds. The Gila conglomerates are double, separated by a period representing present-day conditions.

Summing up the evidences of glacial climate in North America, we find a striking similarity to Europe. In the north elevation and increased land area caused the development of large ice-sheets, which appeared first in the mountainous regions with a heavy snowfall, and later spread over the drier plains and plateaux of the interior. This first glaciation was long and complex. Owing to the anticyclonic conditions which formed over the ice, the rain- and snow-bearing depressions were forced to pass further southward, causing greater snowfall on the mountains and high water-level in the lake basins. This greater snowfall, together with the cold conditions due to the existence of the ice-sheets to the north, caused the development of mountain glaciers south of the main glaciated region. In the east there were cold northerly winds which carried a severe climate as far south as Florida. This Glacial period was followed by subsidence, and a long spell of dry, moderately warm climate lasting perhaps 200,000 years, after which elevation and glacial conditions again set in. These conditions were not so severe as the first, and their duration was much less, while they were broken up by several intervals of temporary recession of the ice, one of which, corresponding to the Riss-Wurm period, lasted for 60,000 years, and perhaps should be considered as an "interglacial." This period was marked in its early stages by the deposition of the curious æolian deposit known as "loess," indicating steppe conditions. After the last glaciation there set in a stage of irregular retreat.

BIBLIOGRAPHY

Leverett, F. "Comparison of North American and European glacial deposits." *Zs. f. Gletscherkünde* 4, 1910, pp. 280, 323.

Wright, W. B. "The Quaternary Ice Age." London, 1914, Chs. 8–9.

Attwood, W. W. "The glaciation of the Uinta Mountains." *J. Geol.*, 15, 1907, p. 790.
Henderson, J. "Extinct glaciers of Colorado." *Colo. Univ. Studies*, 3, 1905, p. 39.
Gilbert, G. K. "Lake Bonneville." Washington, *U.S. Geol. Survey Monograph I*, 1890.
Russell, I. C. "The geological history of Lake Lahontan." Washington, *U.S. Geol. Survey Monograph XI*, 1885.
Coleman, A. P. "An estimate of post-Glacial and interglacial time in North America." *Rep. 12 Internat. Congr. Geol.*, 1913, p. 435.

CHAPTER IX

CENTRAL AND SOUTH AMERICA

The scarcity of data which was bewailed in dealing with Asia is still more marked in the case of South America, and it will be necessary to present the glacial history of that continent in the barest outline only. This is the more unfortunate as the chain of the Andes, extending from north of the equator to high southern latitudes, is of enormous importance in glacial theory, and especially in the question of simultaneity of glaciation in the two hemispheres.

The beginnings of glaciation in South America are obscure. The distribution of animals shows that towards the close of the Tertiary the Falkland Islands were greatly elevated and were united to Tierra del Fuego and Patagonia, and this enlarged land area was connected in some way with Australia and Tasmania, but the mode of this latter connexion is not definitely known. This question will be discussed more fully in Chapter XI; it is sufficient to say here that the amount of elevation may have reached 12,000 feet in Tierra del Fuego. Equatorwards the elevation diminished, and near the equator the land probably lay somewhat lower than now.

In South Georgia the present glaciers greatly expanded, until practically the whole island was buried in ice, and the same is true of the Falkland Islands and Tierra del Fuego, only the highest peaks remaining above the ice. In the latter district there is some evidence of two glaciations separated by an interglacial, the earlier

glaciation being due to a regional ice-sheet and the later to smaller valley glaciers. The intricate coast-line of the Falkland Islands and Tierra del Fuego points to fiord erosion by ice which extended well beyond the present limits of the land, and can only have occurred during considerable elevation. As to the character of the interglacial, little is known. In the Falklands there is a bed of black vegetable soil full of tree-trunks, indicating the existence of luxuriant forests and a temperate climate. This deposit is overlain by boulder-clay, and may be either interglacial or pre-glacial, but since it was formed when the land stood at a comparatively low level, while we have reason to believe (see Chapter XII) that during the close of the Tertiary period these islands were greatly elevated, it is probably an interglacial formation, and indicates a great amelioration of climate. In Gable Island, Tierra del Fuego, Halle found beneath boulder-clay a Quaternary fauna of barnacles and marine mollusca indicating a climate slightly warmer than the present, and this probably belongs to the same period. To the concluding stages of the Glacial period in the Falklands belong the curious "stone rivers," great streams of moss-grown boulders which fill the valleys, and under the influence of temperature changes are probably still slowly advancing.

Passing further north to the Andes, between 39° and 44° south latitude, the glaciation was not so severe, and its records are therefore clearer. The first result of elevation was the cutting of deep canyons by the rivers. This was followed, possibly without much further elevation, by a fall of temperature, which in this connexion may be attributed to the extension of the Antarctic and Tierra del Fuego ice-sheets. Glaciers now developed and spread down the canyons, leaving moraines of great volume and height, associated with all the other criteria of glaciation. The snow-fields from which these glaciers originated lay between 5000 and

6000 feet above the sea, and the snow-line lay at about 3000 feet instead of above 6000 as at present.

This glaciation was followed by a long interglacial, during which the glaciers retreated to the highest summits of the Andes. The length of this period is indicated by the fact that the earlier moraines have been eroded to such an extent that they no longer present distinctly the typical features of glacial topography, while the materials of which they are composed are decayed to somewhat the same extent as the older moraines of North America, the granite boulders especially being rotten and friable. This interglacial was followed by a re-development of the glaciers, but to nothing like the same extent as formerly; their moraines are smaller and fresh-looking, indicating that this glaciation was comparatively recent.

Still further north, in latitude 20°–25° S., we come to a region of very slight snowfall, where the snow-line lies higher than anywhere else on the face of the earth. The glaciation here was comparatively unimportant, the snow-line descending only 1600 to 2500 feet. Here Keidel found moraines of three glacial advances, and from his description it appears probable that the earliest and greatest was separated by a considerable interval from the two younger, the interglacial between which was short and not characterized by a return to present-day climatic conditions, since during this interval there was very little weathering. Probably we have here to do with two glaciations, of which the second was double. In fact, some writers have described no less than five glacial advances in the Argentine Andes, but most of these are probably merely retreat stadia.

In Peru, W. Sievers reports the existence of two glaciations separated by a considerable interval. The present limit of the glaciers is about 15,200 feet; during the first glaciation they descended to about 11,000 feet, and during the second to 12,800 feet. The evidence is very complete. In Ecuador, H. Meyer records a similar

bipartition. The oldest glaciation is represented by trough-like valleys, enormous gravel terraces, and old moraines much weathered; the limits are far below the present limits of glaciers, but have been much obscured by subsequent erosion. This glaciation was followed by a long period of steppe climate resembling the present, during which the loess-like Cangagua formation was deposited. This in turn was followed by a re-advance of the glaciers to a level about 2700 feet below the present limit. This glaciation is associated with crescent-shaped moraines, corrie lakes, hanging valleys and gravel terraces, covered with vegetation, but otherwise fresh-looking. The snow-line lay about 1600 feet below the present. Probably during the first glaciation the Andes were invaded by numerous mountain plants and animals related to North American forms—a valuable piece of evidence which indicates that the glaciation was contemporaneous with that in North America. In Columbia and Venezuela there are traces of Glacial periods, but these have not yet been studied in detail. The most northerly evidence of a Glacial period comes from the Sierra Nevada de Santa Maria, near the north coast of Venezuela in 11° N.

Except in Tierra del Fuego and Patagonia the ice did not extend far from the mountains. But in the eastern Argentine there is a great series of Quaternary deposits known as the Pampean. This formation covers 200,000 square miles, and consists of at least ninety feet of fine loam without a single pebble (except for a few thin calcareous layers), but containing large numbers of complete skeletons of mammals. It raises several interesting problems. Apparently it represents the whole course of the Glacial period. By some geologists it is considered to be a delta deposit of the combined Parana and Paraguay rivers, but the absence of mollusca, except in a marine intercalation near its summit, is against this view, and Steinmann attributes it to æolian agencies and compares it to the loess of Europe and

North America. If this view is correct the Pampean represents steppe conditions prevailing on the equatorial side of the Patagonia-Falkland Islands ice-sheet. Apparently before the incoming of the greatest cold the Pampas were in part at least forest-clad, for in the older beds are found peculiar forms of ground-sloths which were adapted for forest life and have been found also in cave-deposits of Brazil. At the maximum of glacial conditions the Pampas probably had a steppe climate, but the disappearance of the forests is to be attributed rather to drought than to cold. Elevated glacier-bearing Andes to the west and ice-sheets to the south would render the Argentine extremely arid, and this accounts for the gradual extinction of so many giant forms whose remains are found in the Pampean deposits. Conditions ultimately became too severe even for the horse, which died out in South America. The marine transgression which left its mark near the top of the Pampean is probably post-glacial.

In Brazil, on the other hand, there is no evidence that the climate has ever been drier than the present, and in the semi-arid regions of the north-east it is even probable that during the Glacial period the climate was moister, presumably owing to the greater strength of the rain-bearing east and north-east winds. Further west in the Andes the existence of this wet period is borne out by the former greater size of Lake Titicaca, and there seems to be additional evidence to the same effect in the Chilian deserts.

BIBLIOGRAPHY

Steinmann, J. "Diluvium in Südamerika." *Zs. d. D. Geol. Gesellsch.*, 58, 1906, p. 215.

Meyer, H. "In den Hochanden von Ekuador." Berlin, 1907.

Sievers, W. "Reise in Peru und Ecuador, ausgeführt 1909." München und Leipzig, 1914.

Keidel, H. "Ueber den Anteil der Quartaren Klimaschwankungen an der Gestaltung der Gebirgsoberfläche in dem Trockengebiete der mittleren und nördlichen Argentinischen Anden." *Congr. Geol. Internat.*, 12, Canada, 1913, p. 757.

Willis, Bailey. "Physiography of the Cordillera de los Andes between latitudes 39° and 44° S." *Congr. Geol. Internat.*, 12, Canada, 1913, p. 733.

Halle, T. G. "On Quaternary deposits and changes of level in Patagonia and Tierra del Fuego." *Bull. Geol. Inst.*, Upsala, 9, 1908–9, p. 93.

CHAPTER X

AFRICA

The Quaternary history of Africa can unfortunately be dismissed in a very few words. The glaciation of the Atlas Mountains has already been referred to in connexion with the Mediterranean region. Further south we have no great mountain chain such as the Andes extending above the snow-line over the whole extent of the country, but merely a few isolated peaks. Three of these, all close to the equator, are known to show traces of a greatly extended glaciation in the past: Ruwenzori, just north of the equator, on the borders of Uganda and the Congo, reaching an elevation of 16,794 feet, with the present snow-line at 15,000 feet, and glaciers extending to 10,000 feet, formerly bore glaciers extending down as far as 5200 feet; Kenya, on the equator in Kenya Colony, height 17,040 feet, present snow-line about 15,000 feet, past snow-line 12,000 feet, and old moraines at 10,000 feet; finally, Kilimanjaro, 3° S., on the borders of Tanganyika territory, height 19,320 feet, present limit of glaciers 13,650 feet, past limit 4870 feet. Further south, the Drakenberge Mountains, between Basutoland and Natal, were glaciated on their higher summits. In none of these cases have the remains of more than one glaciation been described, but the mountains are still very little known and this negative evidence is not conclusive. In the neighbourhood of Ruwenzori there are several peaks, which approach 12,000 feet, but these were not glaciated, pointing to a snow-line above this level. Unfortunately

the latter piece of evidence is of doubtful validity since these mountains are volcanic and possibly of post-glacial age; we may consider, however, that the glaciation of the central African mountains was characterized by a great increase in the length of the glaciers with only a slight depression of the snow-line, conditions showing that the glaciation was due chiefly to an increase of snowfall, and only in a minor degree to a fall of temperature. This conclusion is borne out by the low-level beds, which nowhere show an appreciably lower temperature, but abound in indications of a former greatly increased rainfall. The first of these is the former greater size of the African great lakes.

Abyssinia, as we have seen, was probably drier than at present, but further south the rainfall must have been considerably greater. Lake Kioga stood 600 feet above its present level, and was connected with Lake Victoria. Lake Victoria and the smaller lakes were twice their present size, and most of the broad valleys were filled with water. Lake Magadi is the attenuated relic of a vast sheet of water, and other great lakes have disappeared entirely. One of these, in the Rift valley, south of Lake Naivasha, has been mapped by Professor Gregory and named after Professor Suess. Part of this decrease of the lakes has undoubtedly taken place within historic times, and part may be attributed to changes in the drainage, but there remains enough evidence to show that some time in the Ice Age the great lakes were very much larger than the present.

Mr. E. J. Wayland, the Government Geologist of Uganda, informs me that in the old basin of Victoria Nyanza there are masses of gravel which may be two or three miles in breadth, the surface of which forms two terraces at different levels. Above the level of these is an old peneplain with ancient beach gravels. Mr. Wayland considers that this peneplain was formed probably during the Pliocene by the first Victoria Nyanza occupying a basin between folds. The initial

high-level was due to the want of an outlet, but may have been amplified by other causes. The level of the lake then sank gradually to a considerably lower level, after which it rose again nearly to its old level and remained there for a considerable time. During this period the great gravel deposits were formed; they contain flood deposits, especially near their base. The level of the lake then sank again and this part of the basin was converted into a valley occupied by a river. Subsequently the level rose again sufficiently to carve out the lower terrace in the gravels. Mr. Wayland considers that the upper terrace may also represent a stage distinct from that in which the gravels were actually deposited, but the upper terrace may be the original surface of the gravels. Thus there is evidence of two Pluvial periods in central Africa, of which the first, probably corresponding with the great extension of the mountain glaciers, was the greater. From the archæological evidence it appears to correspond with the Mindelian glaciation of Europe.

A second line of evidence has been pointed out by C. W. Hobley. At the entrance to Kilindi Harbour, Mombasa, there is a gap in the coral barrier through which the fresh water from the river finds its way. These gaps are always found opposite the mouths of rivers, and are due to the inability of the coral polyp to live in fresh or brackish water. In Pleistocene times the land stood some seventy feet lower relatively to the sea, and the old channel through the reef at this height is almost double the width of the present channel, showing that the river then had a greater volume, i.e. the rainfall in its basin was greater.

But Africa is noteworthy chiefly for its deserts, and the most important evidence of climatic change is found in the deserts of Sahara and Kalahari. From the time of the ancient Greeks it had been believed that the Sahara was formerly the site of a great inland sea, and the presence of this sea had even been suggested

as the cause of the Ice Age in Europe, but recent investigations have shown that this is not so; the Sahara has been land at least throughout the Tertiary period. There is, however, abundant evidence that during the Quaternary the rainfall was considerably greater than the present. The presence of numerous animals closely associated with water, such as the hippopotamus and even the crocodile, in oases now entirely isolated, shows that these oases were formerly connected with the big rivers. The most definite evidence, however, comes from Lake Tchad. This was formerly of much greater area, but Chudeau and Freydenberg have made out a whole series of changes from desert conditions in the Tertiary through pluvial conditions in the Quaternary back to desert conditions of the present. The sequence is as follows:

1. A regime of dunes.
2. A slow transgression causing a long marshy period, during which numerous plants whose remains are found lived in the period.
3. A slow regression.
4. A rapid transgression (grey loam).
5. A slow regression (clayey white loam with traces of roots).
6. A transgression (white loam).
7. Establishment of a new dune regime.

In the Chari basin east of Lake Tchad are the remains of fish and shells, and also small pebbles of sandstone and chalcedony, which are not local, but must have been brought from the mountains of Tibesti by the rivers Egnei and Toro when their current was much stronger than at present. In Senegal, south of the 15th parallel, the present dune sands are underlain by an alluvial soil, indicating moister conditions preceding the present climate. There is no means of dating the moist periods indicated by these phenomena, but it is reasonable to correlate them with the former extension of the central African lakes.

Passing south to the Kalahari, we find evidence of a number of moist stages separated by drier intervals, but they can apparently be grouped into two main Pluvial periods, separated by a long interpluvial with steppe-like conditions. One at least of these Pluvial periods must be correlated with the former immense extension of Lake Ngami and the Etosha Pan.

From Cape Colony there is some evidence of moister conditions in the past, but the Quaternary variations cannot be separated from those of historic times.

Before leaving Africa some reference must be made to an interesting suggestion by C. W. Hobley, as to the mechanism of climatic change in tropical countries. He notes that the north-east and south-west monsoons extend to a height of only a few thousand feet. Above them are the very steady " trade winds " connected with the general circulation of the atmosphere. In Kenya Colony these blow from east or a little south of east. " Their effect is very marked on the high mountains of the interior, such as Kenya, Kilimanjaro and Elgon; in the early morning they are generally quite clear, but about 10 a.m. the clouds sweep up from the S.S.E. and collect on the mountains and blot them out from view for the rest of the day. These are believed to be clouds borne inland by the trade winds, and the moisture they carry is precipitated mainly on the south and south-east sides of the mountains." Hobley suggests that there was formerly a nearly continuous ridge of high land extending north and south, and this caught the moisture from the trade winds, so causing the Pluvial period, the evidence for this ridge being the distribution of alpine plants on the now isolated high mountains. An alternative explanation is that the greater strength of the earth's circulation during glacial times caused the trade winds to be much stronger and also to extend to a lower level at the expense of the monsoons, just as the west winds extended to a lower level in northern Egypt. This would bring a great deal more moisture to be precipitated

on the mountains, increasing the length of the glaciers and also the volume of the rivers.

BIBLIOGRAPHY

Scott Elliott, G. F. "The geology of Mount Ruwenzori and some adjoining regions of tropical Africa." *Q.J.G.S.*, 51, 1895, p. 669.
Hobley, C. W. "The alleged desiccation of East Africa." *Geogr. Journ.*, 44, 1914, p. 467.
Freydenberg, H. "Le Tchad et le Bassin du Chari." Diss. Paris, 1908.
Passarge, H. "Die Kalahari."

CHAPTER XI

AUSTRALIA AND NEW ZEALAND

The continent of Australia has a relatively low relief, only rising above the snow-line in Mount Kosciusko, and glacial traces have a relatively unimportant development. The history of the region appears to be as follows :

In late Tertiary times the shore-line lay some distance to the east towards New Zealand, this being a relic of a much earlier connexion between the two lands. Towards the close of the Tertiary earth movements set in, which elevated the mountain belt of eastern Australia and formed a land connexion with Tasmania and the Antarctic continent. At the same time the land to the east and the closed basins of central Australia were also probably developed about this time. The climate was then somewhat warmer than the present, at least on the east coast, for the Australian barrier reef extended further south. Probably at this time the Antarctic ice-sheet did not reach the sea, and there was none of the floating ice which is such an important factor in cooling the Southern Ocean.

The next stage was the lowering of the snow-line on Kosciusko to about 3000 feet below the present and the development of extensive glaciers, which descended to 5500 feet above the sea, and attained an area of 80 to 100 square miles and a thickness of at least 1000 feet. Tasmania was also extensively ice-covered, probably by glaciers which coalesced at low levels, forming what is known as a " piedmont " ice-sheet, which possibly reached the sea. The lowering of the snow-line in Tasmania is

estimated as 6000 feet, corresponding to a fall in temperature of 18° F. Probably a large part of this fall is accounted for by the increased elevation, which may have been several thousand feet in Tasmania and more than a thousand feet even in New South Wales. This glaciation, which was probably dependent on the growth of the Antarctic ice-sheet, was followed by a very long interglacial, the duration of which has been estimated by Professor David as 100,000 to 200,000 years. The old moraines are much weathered and denuded, resembling in this respect the older moraines of Europe. No information is available as to the climate of this interglacial period. Possibly some of the Quaternary raised beaches with warmth-loving mollusca found in unglaciated parts of Australia belong to this period, and if so the climate was warmer than the present for at least part of the time.

The interglacial was followed by uplift and a second much less severe Glacial period, characterized by valley glaciers on Kosciusko and in Tasmania, reaching the sea in places on the latter island. It was at the close of this Glacial period that man reached Tasmania; its conclusion is dated by Prof. David at about 10,000 years ago. It was terminated by a period of depression below the present level with a warm climate.

In the dry interior of Australia there is evidence that at one time, probably during the maximum glaciation, the rainfall was heavier than the present, and numerous lakes were developed which have now been dry for a very long time. It is possible that the artesian water supply of Australia, which Gregory considers to be "fossil water" accumulated under different conditions from the present, is a vestige of the rainfall of this period. Further north, in Java, the beds in which the famous *Pithecanthropus* skeleton was found, believed to be lower glacial, contain also plant remains similar to those now found in the Khassian mountains of Assam, one of the rainiest climates in the world. The climate of Java

during the maximum glaciation was thus decidedly rainier, and probably somewhat cooler than the present.

An extraordinary find which may be referred to here is that of Professor Neuhauss, who discovered giant erratics, scratched and polished, and moraines at *sea-level* at the western end of Huon Gulf, New Guinea. The region is very unstable, and is known to have stood at a very much higher level, perhaps 10,000 feet or more, in Quaternary times, and if the moraines indicate glaciers terminating at 10,000 feet above the sea they are explicable by a slight fall of temperature and increase of snowfall.

Turning now to New Zealand, we find extensive glacial remains on South Island, though not on North Island. As in so many other countries, the Quaternary opened with great elevation, which reached at least 1500 feet over the whole group. North and South Islands were united with each other, with Stewart Island and probably also the outlying islands, even including the Chatham Islands, forming a great land-mass several times the present area of New Zealand. On the southern part of this land-mass extensive glaciers were formed; on the east these did not reach the present sea-level, but on the snowy south-west they extended far below it, so that the terminal moraines are now completely submerged; possibly they were never formed, but the debris was floated away seaward on icebergs. Further north moraines are found near the present shore line at many places between Milford Sound and Hokitika, and morainic mounds cover a large part of the low ground. Still further north they retreat inland, and in the Nelson Province are not found lobew a level of 2000 feet at the foot of Lake Rotoiti.

In the south-east a great moraine has been described at the south end of Lake Wakatipu and others at the north-east ends of Lakes Manapouri and Te Anau, but none are found nearer the sea-coast. The glaciated area of New Zealand was at least ten times the present

ice-covered area, and the Tasman, the longest glacier in New Zealand, was expanded from its present length of 16 miles to at least 30 miles. Much of the apparent fall of temperature shown by this glaciation was probably due to the great elevation, but apart from this the ice had a marked influence on climate. Outside the limits of glaciation on the east is a thick deposit of typical loess, which extends up to a level of 1000 feet on the flanks of the hills. The occurrence of this loess points to a steppe climate with dry, cold, southerly winds on the lee side of the glaciated mountains, and is probably also connected with the increase of land area. Further north, north of Auckland in North Island, the present treeless plains were covered by forests; for Kauri gum, apparently very old, has been found. The sub-antarctic islands—Campbell, Antipodes, etc.—were not covered by either New Zealand or Antarctic ice, but were the centres of local severe glaciations of their own.

The next stage was a great subsidence, during which the glaciers retreated. The land sank below its present level, raised beaches probably of interglacial age being found at various heights ranging from 10 feet above the sea at Manukau in the centre of North Island to 150 feet at Taranaki, 200 feet at Cape Palliser, 400 feet on the west coast of South Island, 500 feet at Amuri Bluff, and even 800 feet in the entrances to the south-western sounds. This great submergence was associated with the deposition of extensive gravel deposits by the rivers.

The interglacial was followed by a second period of elevation. It is not certain how far this went. Submerged peat bogs have been found at a depth of nearly 600 feet below sea-level near Canterbury, but these may belong to the early stages of the interglacial and not to the post-Glacial period. On the other hand, the submerged forests which are found at many points on the coast of New Zealand are evidently post-glacial and indicate a slight rise above present level. At the same time there was a renewal of the glacial conditions, but the ice

was confined to the valleys and had a much less extent than in the first glaciation. This period seems to have been followed by a slight submergence and a temporary warm period.

BIBLIOGRAPHY

David, T. W. E. "Australasie. Les conditions du climat aux époques géologiques." *Rep. Congr. Geol. Internat.*, 10, 1906, pp. 275–98.
Süssmilch, C. A. "An introduction to the geology of New South Wales." Sydney, 1914.
Gagel, C. "Beiträge zur Geologie von Kaiser-Wilhelms Land." *Beitr. geol. Erforsch. deutsch. Schutzgebieten*, Berlin, 1913, H. 4.
Marshall, P. "The glaciation of New Zealand." *Trans. New Zealand Inst.*, 42, 1909, p. 334.
Salenka, M. L. et al. "Die Pithecanthropusschichten auf Java." *Geol. und Palæol. Ergebnisse der Trinilexpedition* (1907 *und* 1908). Leipzig, 1911.

CHAPTER XII

THE GLACIATION OF ANTARCTICA

THE great Antarctic continent offers a unique problem to the glacial climatologist, for here we have a land area with the theoretical snow-line already at sea-level, and accordingly covered with a thick ice-sheet that leaves only a few mountain ranges and nunataks exposed above its surface, and yet in the past these ice-sheets and glaciers have attained a thickness several thousand feet greater, and have extended further north. Various suggestions have been made to account for this former extension, perhaps the most remarkable being that it coincided with a milder and therefore snowier climate. This, however, is untenable, for the Glacial period of Graham Land and the South Orkneys is obviously a southward extension of the Glacial period of Tierra del Fuego, which was obviously due to a colder climate, and can be traced northward along the Andes into tropical regions. A more fruitful suggestion is that as one of the most potent factors in preventing the accumulation of snow is at present the wind, it was a decrease in the strength of the wind which enabled the ice to reach a greater thickness. This is probably true in a sense, the decrease of wind force being due to a great increase in the area of the Antarctic continent during the Quaternary.

We have seen that in the early Quaternary there was great elevation in the south of South America and also in Australia and New Zealand. The amount of this elevation increased southward and was very great near

the polar circle. This is borne out by considerations based on the distribution of living and fossil animals, which point very definitely to a land connexion between Australia and South America in Tertiary and early Quaternary times, most probably by way of Antarctica.

The first line of evidence is the distribution of the marsupials, living and extinct. As is well known the chief home of this type of mammal is now in Australia and New Guinea, but in Tertiary deposits in Patagonia remains of extinct forms known as Dasyurids have been found, which are allied to Australian forms, and can only have come from Australia, probably via Tasmania. Secondly, there are two peculiar families of fresh-water fishes, the *Haplochitonidæ* and *Galaxiidæ*, the first common to Australia and South America, while one species of the second is found in New Zealand, Tasmania, the Falkland Islands and Patagonia. Thirdly, Beddard has found an intimate relation between the earthworms of New Zealand, Eastern Australia and Patagonia. Finally there is a curious similarity between the slugs of Patagonia and those of Polynesia.

What is the explanation of these relationships? Assuming that there has been a land-connexion, it can have been either by way of Antarctica or Polynesia. The earthworms cannot endure a very severe climate, but on the other hand there is a total absence of any tropical forms common to Australia and South America, and the general dissimilarity of the faunas shows that the connexion cannot have been available for a very long period. A study of the oceanic depths suggests that the Antarctic connexion is the more probable. A comparatively slight elevation would connect Patagonia and the Falkland Islands with the South Shetlands and Graham Land, and an elevation of 12,000 feet would give a large land connexion between Australia and the opposite coast of Antarctica via Kerguelen. Forbes even postulates an immense Tertiary Antarctica in which several forms of

animals and plants were able to evolve, but except possibly in the case of the edentates this supposition is not necessary.

The course of events may provisionally be taken as follows: In late Tertiary times an elevation of at least 12,000 feet in the South Polar regions caused a great increase in the area of Antarctica, which was united to South America on the one hand and Australia on the other. The northern shores of this continent were far to the north of their present position, and though the interior was very cold the coast lands had at first a moderate temperature, and for a short time allowed animals to migrate from Australia to South America or vice-versa. But the high mountains of the interior were already glaciated, and ice-sheets gradually crept down their slopes. Owing to the small precipitation the advance of the ice-sheets was slow, but ultimately, probably in late Tertiary times, they approached the coast, and the track along which migrations had taken place was closed. The distribution of animals and plants shows quite clearly that the land connexion was maintained into the period of refrigeration. The shores of the continent being further north, the pressure gradient between the pole and the present coast was less, and consequently the winds were lighter. This and the diminished loss by calving into glaciers allowed the ice to become thicker than it is now.

Hedley apparently considers that the migrations referred to above took place in an interglacial period, but the Patagonian beds in which the fossil marsupials are found are Tertiary and not Quaternary. No direct evidence of an interglacial period has been found in Antarctica, nor, considering the intensity of the glaciation which the country is even now undergoing, is any such to be expected, and we can only infer from the bipartition of the Glacial period in Australia, New Zealand and South America—which, in New Zealand at least, was associated with submergence—that there was probably a

similar bipartition in Antarctica. Nordenskjold states that the submarine relief showing river erosion which, in Tierra del Fuego, was developed partly at least in the interglacial period, is also developed in West Antarctica. It is improbable that the ice ever entirely vanished from the continent. We shall see in Chapter XIV that even the comparatively brief warm period known as the post-glacial climatic optimum extended to the Antarctic coast, and this is additional argument for extending the much greater interglacial oscillation southward beyond its known limits in Tierra del Fuego, Australia and New Zealand, but here the matter must be left.

BIBLIOGRAPHY

Hedley, C. "The palæographical relations of Antarctica." London, *Proc. Linnæan Soc.*, 124, 1911–2, p. 80.

Lydekker, R. "A geographical history of mammals." Cambridge University Press, 1896, pp. 125 ff.

David, T. W. E. "Antarctica and some of its problems." London, *Geogr. J.* 43, 1914, pp. 605–30.

Nordenskjold, O. "Antarktis." *Handbuch Regional Geologie*, Heft 15, 1913.

CHAPTER XIII

THE CLOSE OF THE ICE AGE—THE CONTINENTAL PHASE

In Chapter V we left the climatic history of northern Europe at the point where the ice in its final readvance had once more reached the German coast. But Scandinavia was now sinking, and the margin of the ice soon began to retreat again. At the same time the Alpine glaciers diminished in size, while the Irish and Scottish glaciers disappeared. This is the critical period in the change from glacial to temperate conditions, and, thanks to the researches of the Swedish geologists, and especially G. de Geer, H. Munthe and Gunnar Andersson, we are very well acquainted with it. The change was not uniform ; at first the recession was very slow, and there were periods when for scores of years the ice-edge remained stationary or even readvanced, but on the whole the time was one of persistent amelioration. The following description is based chiefly on W. B. Wright's summary of de Geer's work.

After leaving the coast of Germany the ice-edge appears to have remained in the western Baltic, retreating slowly for some 8000 years. About 10,000 B.C. it lay along the southern coast of Sweden, and during the next 2000 years it withdrew to about 59° N. This was the Gotiglacial stage. Here came a pause, when, for 200 years, about 8000 B.C., owing presumably to a change for the worse in the climate, the ice-edge remained in one position, forming a great moraine. Then came another period of very rapid retreat, the Finiglacial occupying nearly 3000 years, followed by a

further halt of some duration near Ragunda, about 5000 B.C. After this the ice-sheet split into two portions, and the Glacial period is regarded as over.

In the Alps there were similar periods of regression and of halting or readvance. The first, known as the Buhlstadium, corresponded to the Baltic readvance (Chapter V). The second, the Gschnitz-stadium, with a snow-line 2000 feet below the present (i.e. mean temperature about 6° F. lower than now), has not been dated, but probably occurred about 8000 B.C. This was followed by a warmer period, probably as warm as and drier than the present, after which the glaciers readvanced about 5000 B.C. in the third or Daun-stadium, when the snow-line was depressed 1000 feet (temperature 3° F. lower than now).

In the lower Nile valley the deposition of gravel ceased, and that of mud began about 8000 B.C., indicating that at this time the climate of north-east Africa reached its present state of dryness.

It is at present difficult to give more than a tentative explanation of these oscillations of climate during the Retreat Phase. Northern Europe was at the time passing through a complicated series of geographical changes. As the ice left the Baltic basin the latter became the site of a cold ice-lake, with narrow outlets to the Atlantic by way of the Sound and the Belts. At this time the recession was slow. Then the retreat of the ice opened a connexion with the White Sea, and elevation closed the outlet to the west. This probably made the waters still colder, and the Fennoscandian pause occurred. Elevation now closed the connexion with the White Sea, and an entirely closed-in ice-lake resulted. During this stage the retreat was slow, until between 7000 and 6000 B.C., when the ice-sheet vacated Scania, and direct communication between the Baltic and the Atlantic was opened across Lakes Wener and Wetter, and the climate, though still arctic at first, became appreciably warmer by 6000 B.C.

For more than 10,000 years of the retreat, or until 6000 B.C., the ice-sheet was still sufficiently large and powerful to maintain a border of Arctic anticyclonic conditions on its southern edge. During the retreat the mean annual temperature of southern Sweden increased from 17° F. to 35° F., equivalent to a change from North-east Greenland to South Greenland. The July temperature rose to about 43° F. On the North German Plain still lived the reindeer and the fauna and flora of the sub-Arctic tundras; the mean annual temperature rose to 45° F. by the close of the period. The land flora in Sweden was entirely xerophilous, indicating a slight rainfall. There is also geological evidence of a small annual rainfall on the south-west coast of Norway. This period covers the transition from Palæolithic to Neolithic culture.

It seems probable that the continental character of the climate of the final stages of the retreat phase was slightly increased by astronomical causes, the obliquity of the ecliptic being probably nearly one degree greater about 7500 B.C. than it is now. In Germany and Sweden this would have the effect of lowering the winter temperature and raising the summer temperature by rather more than 1° F.

While the land was still falling rapidly in the north of Scandinavia and the Gulf of Bothnia, the coasts of Germany and Denmark began to rise, and about 6000 B.C. again closed[1] the outlet of the Baltic, converting it into a large fresh-water lake, the *Ancylus* lake. A similar lake was formed farther east in central Finland. At this time the south-west Baltic lands stood more than 100 feet higher than at present. The land was probably still largely under the influence of dry easterly winds, and the shutting out of the Atlantic accentuated the continental conditions, and this stage in the climatic history of Europe is known as the "Continental Phase." The winter climate was severe; at first the summers were not especially warm

[1] See reference to Antevs in this connexion.

(July temperature about 54° F. in southern Sweden). This is probably the period of formation of the Ragunda moraines, and of a readvance of the glaciers on the Norwegian side of the divide, when the snow-line lay 200–300 metres lower than at present; it was also the time of the Daun readvance in the Alps. But as the land sank in the north and rose in the south, the waters of the *Ancylus* lake retreated farther and farther north, and the summers became hot and dusty, with a mean July temperature of about 60° F. Everywhere in the Baltic regions the older *Ancylus* beds show a monotonous pine-wood, but in the upper *Ancylus* these are followed closely by a number of plants and shrubs of southern type—black alder, curled birch, linden, etc. The temperature continued to rise, and oak, Norway maple, ash, and finally, in the southernmost parts of Sweden, the common maple appeared. The last-named plant has been found below the present level of the sea in Ystad Harbour.

Under the influence of these conditions the remnant of the Scandinavian ice-sheet again decreased in size, until it split into two portions, the break occurring at Ragunda, and this is considered by Scandinavian geologists to mark the end of the Ice Age in Europe. Gunnar Andersson compares the climate of southern Sweden at this time to the Baraba Steppes in western Siberia, with an annual rainfall of 12 to 16 inches, but this seems an extreme estimate. The "Karst" flora of the limestone areas of south-east Europe immigrated into eastern Sweden during this period, and south-east Europe probably gives a better idea of the climate of Sweden during the continental phase. Farther east, in Finland, Kupffer describes the climate as resembling that of central Russia. In central Germany the climate was dry, with a mean temperature in the four summer months of 63° F.; it resembled that of south-west Russia. This period of warm summers began earlier in Germany than in Sweden, and throughout this phase

Scandinavia was occupied by a rich forest flora. The hazel extended several degrees north of its present position, and to higher levels, indicating a July temperature about 7° F. higher than the present. In southern Norway the pine extended to much greater heights. But the ivy and yew, whose limits depend on the winter rather than on the summer temperature, showed no such extension, indicating that the winters remained severe. In Denmark there was a dry climate, fairly warm at the close, with fir forests, though western Denmark is now too wet for this tree. On the coast of Norway the seas were still cold, so that there is a contrast between the animal life of the sea and the plant life of the land. The Alps also became warm and dry, and were occupied by a xerophilous flora.

As the glacial anticyclone decreased in intensity, depressions from the Atlantic began to take a more northerly course, but were held up near the British Isles and materially increased the rainfall. This is the first peat-bog period of these islands, when the birch and pine forests which had covered the non-glaciated lands during the cold dry period gave way to extensive growths of peat-bogs. Southern and eastern England, however, largely escaped this damp period, sharing in the dry climate of the Continent.

The absence of storms off the north-west coast of Norway is shown by the forests which at this period covered all the outermost islands of Norway as far as Ingo Island, off North Cape. These islands are now barren, and their afforestation indicates a drier and especially a less stormy climate than the present, with a decreased frequency of winds from the sea. These conditions were well developed about 5000 B.C. This is the Early Neolithic period. Owing to the great development of forests, this period is sometimes called the *Early Forest period.*

The late glacial history of North America was equally complicated. Consider first the region of the St.

Lawrence Estuary and the Great Lakes. As the Wisconsin ice-sheet retreated across the present site of the Lakes, the latter underwent a remarkable series of fluctuations of area and outflow, which have been made the subject of brilliant studies by several American geologists. The opening stage began when the ice abandoned the high ground south of the lakes, leaving depressions bounded on the south by the hills and on the north by the ice. The earliest of these in the basins of Lakes Erie and Huron are known as the first and second Lake Maumee. These gradually grew in size and coalesced, forming several series of connected lakes, to which various names have been given; thus Lake Warren extended well outside the present limits of Lake Erie and southern Huron, and was held up by ice over Lake Ontario and northern Huron. At a later stage an enormous Lake Algonquin extended beyond the combined limits of Lakes Superior, Michigan and Huron, and communicated by broad channels with an enlarged Lake Ontario known as Lake Iroquois, and with Lake Erie. But even before this time the northern shores of the lakes, relieved of the major portion of their ice-load, had begun to rise rapidly, and ultimately reduced the lakes to their present size.

These great areas of ice-cold water, bathing the southern edges of the ice-sheet, must have had an unfavourable influence on the climate, keeping it cold and damp, and preventing dry continental conditions from becoming established. They probably retarded the ice-retreat in these regions quite considerably, so that a lobe of ice was left here long after the edge had retreated northwards on either side. At the same time the climate further south was dry, with æolian deposits; but as the anticyclonic winds blew off the Atlantic the evidence of drought is not so marked as in Europe.

After this slow retreat had been in progress for a considerable time a submergence, known as the "*Champlain stage*" set in, reaching a depth of at least 600 feet and

opening the St. Lawrence regions wide to the Atlantic, which penetrated into Lake Ontario. The ice now retreated rapidly under the influence of a maritime climate little colder than the present. In phase this period corresponds to the second *Yoldia Sea* stage of Scandinavia; in point of time it was probably somewhat earlier. This was followed by elevation, the first result of which was to cut off the warm water and cause a sharp fall of temperature exactly analogous to that of the Ragunda moraines, but a few thousand years earlier and probably more marked. The continuance of elevation brought on a long continental period of extreme aridity, when tree grew on the peat-bogs of the eastern States, while the lakes of the Great Basin further west were almost or wholly dried up. At the maximum of the continental conditions the summers at least were warmer than at present, as indicated by the northward extension of various species of plants and fresh-water mollusca. The winters were probably more severe. Possibly the great aridity of this period was partly due to a sub-glacial continental anticyclone obstructing the path of depressions across America from west to east. The drainage area of the Great Basin received hardly any rainfall and was a hopeless desert, but the Atlantic States were able to grow trees on the old peat-bogs, probably with rainfall derived from the Atlantic. By reference to the cutting of Niagara gorge, we can infer that the warm dry period began about 6000 B.C., so that it corresponds exactly with the continental phase (*Ancylus* stage) of Europe. This period of aridity was finally ended by a fresh submergence, the "*Micmac*," which carried the land about twenty feet below its present level.

In Yukon and Alaska, where the glaciation was not nearly so severe as further to the south-east, the depression of the land by the ice-load and consequently the subsequent rise on its removal were not great. There were no complicated geographical changes, and correspondingly there appear to have been no fluctuations

of climate, but only a gradual passage to present conditions.

Even in Iceland there are indications of a dry period following the last glacial maximum, for tree-trunks, buried in the peat-bogs, show that the birch formerly had a much greater extension. It is also quite possible that there was an accentuation of desert conditions in Asia during the retreat of the glaciers in Europe and North America, which may have played a part in the wave of Neolithic migration that appears to have overwhelmed the artistic Palæolithic races of western Europe; but of this we have as yet no direct evidence. The Neolithic invasion of Europe took place along two main routes, the Nordics passing from the centre of Asia north of the Caspian, across Russia to the Baltic shores, where they became the Kitchen-midden people; and the Alpine race passing from Transbaikalia, south of the Caspian and Black Sea, into southern Europe. The Nordics drove before them an older race, characterized by the transitional Maglemose culture, which passed from east of Russia to the shores of the Baltic and ultimately to England, where harpoons of Maglemose type have been found beneath the peat of Holderness.

In the southern hemisphere the continental phase does not appear to have been so well developed. The uppermost part of the Pampean loess is possibly post-glacial; more certainly so are the sand-dunes on the coast near Buenos Aires, in which human remains have been found in association with the bones of some extinct animals. In New South Wales, after the retreat of the glaciers, there was a period with land a little above its present level, so that the stools of Eucalyptus trees are now found ten feet below sea-level; but there is no evidence as to the climate of this stage. In New Zealand we have no definite post-glacial beds of continental type. The occurrence of xerophilous plants, such as *Aciphylla*, still living in a climate which is now decidedly moist, may be a remnant of a continental phase in New

Zealand, or may date back to the steppe conditions of the loess. As to Antarctica, we have, of course, no evidence.

BIBLIOGRAPHY

Brooks, C. E. P. "The evolution of climate in north-west Europe." London, *Q. J. R. Meteor. Soc.*, 47, 1921, p. 173.

Wright, W. B. "The Quaternary Ice Age." London, 1914. (Ch. 17, Late-glacial changes of level in North America.)

Bericht Internat. Geologenkongress, Stockholm, 1910. "Die Veränderungen des Klimas seit der Maximum des letzten Eiszeits." Numerous papers, dealing with Europe and North America.

Munthe, H. "Studies in the Late-Quaternary history of southern Sweden." Stockholm, *Geol. Foren. i Forh.*, 22, 1910, pp. 1197–1292.

Antevs, E. On the late-glacial and post-glacial history of the Baltic. *Geogr. Rev.*, New York, 12, 1922, p. 521.

CHAPTER XIV

THE POST-GLACIAL OPTIMUM OF CLIMATE

In most of the polar and temperate regions of the world the Glacial period seems to have been separated from the present by a short interval of slightly more maritime climate. The existence of this phase was the chief point brought out in the great collection of papers communicated to the Stockholm meeting of the International Geological Congress, which has frequently been referred to in this volume. The pioneer work on the subject has been done by the Scandinavian geologists, and we may commence with a discussion of this period in the countries bordering on the Baltic.

About 4000 B.C., at the conclusion of the continental phase referred to in the preceding chapter, a rapid movement of submergence set in over the whole of the southern Baltic, and shortly afterwards the land-bar which had formerly separated the fresh waters of the *Ancylus* lake from the Atlantic gave place to a wide strait, through which the waters of the ocean flowed into the Baltic across southern Sweden. Ultimately this channel became wider than the present outlet between Sweden and Denmark, and maritime influences penetrated to all parts of the Baltic. In recognition of this influence the period was termed by Blytt the "Atlantic stage." The much greater freedom with which the waters of the Atlantic were able to enter is shown by a comparison of the "isohalines" of this period with those of the present day. Isohalines indicate the degree of saltness of the water; those of to-day can, of course, be measured

directly, and show that in the Gulf of Bothnia the water becomes continually less salt as we go northward, for which reason many species of marine mollusca are unable to live. By studying the distribution of the mollusca in the *Littorina* Sea the isohalines of that period have been reconstructed also, and show that the salt content was much greater than at the present day, indicating a greater influx of oceanic waters.

If we take a map showing a reconstruction of the geography of *Littorina* time, and apply to it the formulæ given in the Appendix, comparing our results with the inferences of Scandinavian and north German geologists as to the temperature, we find that there is a remarkably good agreement. Many of the palæo-botanists comment on the prolongation of the autumn into the present winter, which is especially characteristic of a more insular climate. The amounts of change in each case are also in good agreement, except perhaps in the Christiania region and in north Denmark, where the geologists require a greater change than that calculated from the land and sea distribution; this is probably accounted for by a higher temperature in the waters of the Atlantic. The maximum change as calculated is shown in south-west Finland (winter 6° F. warmer, summer 2° F. cooler). Finland is described as having at that time the climate of western Europe, which we may take as meaning winter 8° warmer, summer 3–4° cooler. There was thus a great change from the extreme climate of the continental phase with its hot summers and severe winters and little rain, to an extremely temperate climate with cool summers, mild winters and a heavy rainfall. The warmth-loving plants which had begun to immigrate during the later part of the continental phase continued to spread, and probably the highest average temperatures were reached at the time of maximum submergence, but now they were accompanied by plants for which a large rainfall is necessary, and it seems that the average rainfall of southern Sweden

must have been about 40 inches a year. The oak began to dominate the forests in place of the hazel, and the peat-bogs, which during the preceding dry period had hardened into a firm surface on which birch and pine were able to take root, again became moist, so that the trees were choked by growths of bog-plants. On the shores lived men of the Transition and Early Neolithic. As the land rose again and the *Littorina* Sea decreased in area the climate again became drier and more rigorous. In Denmark the forests of the *Ancylus* period gave place to oak as the land sank, and there are also remains of two water plants, the water-nut (*Trapa natans*), which is no longer found in Denmark, and *Najas marina*, still living in one isolated locality. Northern Denmark was broken up into islands, among which marine deposits were formed, containing the remains of southern mollusca, many of which are found in the kitchen-middings. Most of the wood used by Neolithic man was oak; there is little fir and no beech.

In Norway the work of C. Brögger has made us familiar with the *Tapes* beds, which correspond in point of time to the *Littorina* stage of the Baltic. *Tapes decussatus* is itself a southern species of mollusc, and it is associated with a very rich warmth-loving fauna. In southern Norway the geographical conditions were different from those in Sweden, for the land reached its lowest level relatively to the sea about the close of the Glacial period, and has been rising throughout the post-glacial. The seas show a progressive rise of temperature from 8° F. below present at the close of the Glacial period to 4° F. above the present in the older *Tapes* beds. The littoral climate at this stage resembled that prevailing at present on the coast of northern England. After this, as the land approached its present level, the temperature fell again, and in the upper *Tapes* stage was only 2° F. above the present.

The warm period represented by the *Tapes* beds is found at intervals along the west coast of Norway, and

we again find evidence of a submergence of the land contemporary with the maximum temperature. These conditions extend even as far north as Tromsö, within the Arctic circle. In Spitzbergen there are raised beaches 30 to 80 feet above the sea, containing remains of molluscs and a species of *Fucus*, none of which are now living so far north. On the land there are old peat-bogs of great thickness, though peat mosses cannot now grow, since the ground never thaws below a depth of 6–10 inches. It has been pointed out that a great number of the plants now living in Spitzbergen are unable to ripen their seeds under present climatic conditions, though they must have done so in the past. Ripe seeds of some species, in fact, have been found in the peat-bogs, which are contemporaneous with the raised beach. There is thus evidence of a very well-marked warm period associated with submergence in Spitsbergen.

In Franz Josef Land, Nansen found raised beaches with mussels 10 to 20 feet above the present level; this shell does not now live so far north. In the White Sea and on the Murman coast there are also raised beaches with a southern fauna. The warm period shown in the beds of the New Siberian Islands has already been referred to (p. 79).

Returning to the British Isles we find that in the south the land was above its present level throughout the whole of the post-glacial period. On the other hand, a 25-foot beach is found in north-west England (Formby and Leasowe marine beds), but without any evidence as to climate; the same applies to the 25-foot beach of Scotland. It is only when we come to the north-east of Ireland that we find evidence of conditions appreciably warmer than the present, in the section of the Alexandra Dock, Belfast, where marine clays overlie beds of grey sand and peat. The lower estuarine clay is essentially a littoral clay, known as the *Scrobicularia* zone. It is brownish-blue and sandy, and contains in abundance the roots and leaves of the grass-wrack

(*Zostera marina*), and a vast number of shells of a few species which live between tide-marks, indicating that the land stood 10 feet or so above its present level at first, while the climate cannot have differed greatly from that prevailing at the present day. It must have been formed during a period of gradual depression, for throughout its six feet or more of thickness it preserves identical littoral characters. After a time this depression became more rapid, and the upper estuarine clay began to form—a light blue clay, very pure and unctuous, with a very rich and well-preserved fauna, known as the *Thracia* zone. The fauna has a decidedly southern aspect, and indicates that the coasts of north-east Ireland had the present temperature of Bantry Bay—an increase of at least 3° F. in the mean annual temperature. The *Thracia* zone is followed by a bed of yellow shore sand, indicating re-elevation to about seven feet above the present level.

Corresponding to the upper estuarine clay are raised beaches at a height of 25 feet in north-east Ireland, falling to 15 feet at Dublin, and to only 6 or 7 feet in western Donegal and Sligo. The mollusca indicate a somewhat higher temperature than the present. In the beaches have been found flint scrapers and arrowheads of early Neolithic type.

Looking further westwards, we find that Iceland, which had undergone a slight elevation during the continental phase, so that peat was formed below present sea-level, again subsided, falling to 10 or 12 feet below its present level. During this subsidence the temperature rose, the greatest warmth coinciding with the lowest level of the land. Species from the south-west shores, where the temperature of the water is directly influenced by the Gulf Drift, extended to the cold northern coast. In some places the marine clays of this period have been ploughed up by a subsequent readvance of the glaciers.

From Greenland comes abundant evidence of a post-

glacial warm period coincident with a subsidence of about 80 feet. Raised beaches all along the west coast contain mollusca, some species of which are not now living north of the St. Lawrence estuary. On the other hand, some northern species which lived off the west coast during the glacial maximum retreated northwards during this period, and have not re-established themselves, though the climate is now suitable. Further, K. Steenstrup describes the occurrence of " dead ice " at several places in North Greenland—masses of ice which have become separated from their parent glaciers owing to rapid recession, and are now buried in morainic matter. Subsequently the ice again advanced, and in some cases a new glacier has advanced over these masses of " dead ice."

Passing to the mainland of North America, we find in eastern Canada colonies of southern mollusca, especially oysters and quohogs, separated from their main area of distribution south of Cape Cod by a wide area of cold seas—the Gulf of Maine and Bay of Fundy. At the beginning of the warm phase the land lay slightly below its present level, but subsequently rose above it. The climate became still warmer, until its temperature resembled that of the middle New England States. At the same time the rainfall diminished and the peat-bogs were replaced by forests of hardwood trees. In the basin of the Great Lakes the warm period is represented by gravel beds in the Niagara gorge, which from their position must, according to the most recent determinations, have been formed about 4000 to 3000 B.C. These gravels contain shells of fresh-water mollusca, especially species of *Unio*, which are not now living in the St. Lawrence system, but are found in tributaries of the Mississippi further south. Further south on the eastern coast of the United States there are marine deposits indicating a slight submergence, with a climate somewhat warmer than the present.

Passing to South America, we find in southern Pata-

gonia and Tierra del Fuego exactly similar evidence of a post-glacial subsidence with a warmer climate than the present. Raised beaches at a height of 50 feet contain mollusca, some of which are now rare or extinct in that locality, and in sheltered situations plants are found still living whose nearest neighbours are some way to the north.

In the same way, in southern and eastern Australia there are beaches a few feet above present level, containing warmth-loving species of mollusca and indicating a post-glacial warm period. There is some evidence in the distribution of plants and marine mollusca that this warm period extended to New Zealand. Raised beaches at a height of 50 to 180 feet are also known from many places in Antarctica, and these contain mollusca, some of which are not now living south of the sub-antarctic islands. An interesting confirmation of this has been given by E. Philippi, from the results of an examination of the sea-floor at four points in about 63° S., 75–95° E., all within the present limit of pack ice. The deposit at present forming is poor in pelagic foraminifera, and consequently contains little lime, but this deposit is very thin, and beneath it is a much more calcareous clay especially rich in *Globigerina*. The latter deposit is still forming north of the limit of pack ice, and Philippi concludes that at no very distant date the limits of ice were further south, indicating warmer conditions. It is interesting to note that a similar sequence has been found in the Norwegian North Sea, the brown foraminiferous deposit (in this case containing *Biloculina*) being known to be underlain as well as overlain by an unfossiliferous grey clay attributed to the Glacial period. Finally, with regard to Cape Colony, A. W. Rodgers says: "It is possible that the presence of marine mollusca belonging to species that are only known in the living state from the coast north of Pondoland, in the raised beaches of Mossel and Algoa Bays, indicates that the sea on the south coast was formerly warmer than now."

Thus we have evidence of a period of submergence and climates warmer than the present from a large number of places, including the Arctic Ocean and Greenland, the temperate coasts of North America and Europe, the Southern Ocean and Antarctica. The stage appears to be missing on the temperate coasts of the Pacific, on both the Asiatic and North American sides, and from the whole of the Tropics. It is fairly certain that the warm period occurred at the same time in eastern North America and western Europe ; in the case of the southern hemisphere we have no direct proof of this, but in all cases the deposits are comparatively recent, and since they obviously refer to a similar state of affairs we may assume that they are of the same date.

In the Baltic area we know that the great change of level was due largely to a subsidence of the land and only to a small extent to a rise of the sea. But in other parts of the world the amount of submergence was remarkably uniform at places in the same latitude, and decreased steadily from the polar regions to about latitude 40–50°, where it became zero. Now such a general change suggests that it was the sea which rose rather than the land which sank, and points to some general cause which piled up the waters of the oceans in the higher latitudes. A possible cause of this nature has been adduced by O. Pettersson, which he terms the "tide-generating force," which reached one of its maxima in an 1800-year cycle about 3500 B.C. This possibility will be dealt with more fully in Chapter XVII.

BIBLIOGRAPHY

Bericht Internat. Geologenkongress, Stockholm, 1910. "Die Veränderungen des Klimas seit der Maximum des letzten Eiszeits." Numerous papers ranging from the Arctic to the Antarctic.

Brooks, C. E. P. "The evolution of climate in north-west Europe." London, *Q. J. R. Meteor. Soc.*, 47, 1921, p. 173.

Praeger, R. Ll. "Report on the estuarine clays of the north-east of Ireland." *Proc. R. Irish Acad.*, ser. 3, Vol. 2, 1892, pp. 212–89.

Goldthwait, J. W. "The twenty-foot terrace and sea-cliff of the lower St. Lawrence." *Amer. J. Science*, ser. 4, Vol. 32, 1911, pp. 291–317.
Cowles, H. C. "A remarkable colony of northern plants along the Apalachicola River, Florida, and its significance." *Rep. 8 Internat. Geogr. Congress*, 1904, p. 599.
Shimer, H. W. "Post-glacial history of Boston." *Amer. J. Science*, ser. 4, Vol. 40, 1915, pp. 437–42.
Halle, T. G. "On Quaternary deposits and changes of level in Patagonia and Tierra del Fuego." *Bull. Geol. Inst.*, Upsala, 9, 1908–9, pp. 93–117.
Süssmilch, C. A. "An introduction to the geology of New South Wales," Sydney, 1914.
Marshall, P. "New Zealand." *Handbuch regional Geologie*, Heft 5, 1911.

CHAPTER XV

THE FOREST PERIOD OF WESTERN EUROPE

Hitherto we have been dealing with climatic changes which can be recognized with more or less certainty over most of the polar and temperate regions of the world, but we have now to describe a stage which appears to have been peculiar to Europe and possibly Asia—the Forest period. By 3000 B.C., or towards the close of the Neolithic period, considerable elevation had again taken place over the central latitudes of western Europe (the northern parts of Norway and Sweden were still several hundred feet below their present level). The southern part of the British Isles, which had remained slightly elevated since the last Glacial period, had now emerged to a height of nearly ninety feet above its present level; the area of Ireland had increased appreciably and part of the North Sea was land. The geographical changes were not great, but they were sufficient to turn the scale in the direction of a continental climate in the British Isles. The more or less complete closing of the Straits of Dover, and the consequent bar to the free circulation of the Gulf Drift, must have had an appreciable effect on the climate in the direction of continentality. At the same time the low level of northern Norway, and possibly the persistence of warm conditions in the Arctic basin, more and more attracted depressions to the northernmost track, so that the British Isles especially, and to a lesser extent Holland, Germany, southern Scandinavia and Russia, came more persistently under the influence of anticyclonic con-

ditions. The rainfall of these countries diminished, and the surface of the bogs dried sufficiently to enable forests to grow in the western countries; in Germany heath-plants took the place of bog-plants, while in Russia steppe conditions supervened. The normal meteorological conditions at this time in fact resembled those of the memorable drought of 1921, which was characterized by low pressure and stormy conditions in the Arctic Ocean and a belt of high pressure and persistently fine weather across central Europe.

During this phase the winters may have been severe, but the summers were warmer than the present, for in the peat-bogs of Ireland and Scotland are the remains of trees larger than any now found in the neighbourhood. The Irish bogs dried so completely that they were extensively inhabited; corded oak roads have been found at this horizon, while in 1883 a two-story log house, surrounded by an enclosure, was found in Drumkelin Bog, Co. Donegal; it was twelve feet square and nine feet in height, and a roadway led to it across the bog. Both house and roadway were entirely constructed of oak. With the hut were found a stone chisel and a flint arrowhead. Beneath the floor were fourteen feet of bog, and above the floor twenty-six feet. This time was also one of relatively little wind movement, for stools occur even in exposed positions on the mountain slopes of western Ireland, where trees will only grow now in sheltered positions near sea-level.

Further evidence of the very dry climate of this phase is the frequent occurrence of trees apparently *in situ* beneath the surface of fresh-water lakes, both in Ireland and Scandinavia. I was able to examine one very good example near Lough Toome in north-west Ireland. An unusually dry spring had lowered the surface of the water and a large number of tree-stools were exposed; when these trees were growing the water-surface must have been at least two feet below the level of the present outlet. Most of the lakes in which these stools are

found are shallow upland basins with a small drainage area, and if the present climate became drier they would more or less completely disappear.

Mr. Fairgrieve has noted the action of blown sand on the westward side of broken-off tree-stumps in a submerged forest on the shore in south Wales, which, though not conclusive, suggests dry conditions. Mr. Fairgrieve also noted the direction of fall of twenty-one trees, and found that in the great majority of cases they were blown down by westerly winds.

The forest phase was short; according to the late C. Reid the land again began to subside shortly after 3000 B.C., and by 1600 B.C., in Britain at least, had reached its present level; this carries us to the beginning of the Bronze Age. In connexion with Ellsworth Huntington's theory that the dampness of Ireland lowers the energy of its inhabitants, it is interesting to note that this dry period apparently corresponds to the legendary Heroic Age, when the vigour of the Irish reached a level never since attained. Civilization in Scandinavia also seems to have benefited by the drier conditions, for Scandinavian technique advanced rapidly to a high level about 1800 B.C. But though there is evidence of a considerable sea-borne commerce with Britain and Ireland, there appears to have been comparatively little land traffic between different parts of Scandinavia at this time. In fact, to primitive man dense forest with thick undergrowth was almost impenetrable. But at the close of the forest phase and the beginning of the peat-bog phase the trees were weakening under conditions becoming unfavourable. Such dying forests are marked by the absence of undergrowth and young trees, and afford safe and easy land communication. Accordingly we find that by 1500 B.C. a considerable traffic had developed across Scandinavia by land.

Although we have no direct evidence, the meteorological conditions suggest very strongly that the dry belt extended across Russia into Siberia as a marked

period of desiccation, possibly worse than any droughts of the historic period. At present Siberia receives its rainfall mainly from depressions which cross Russia from the Baltic or Black Seas, and follow a well-marked track north of the central Asiatic mountains. But during the forest period these tracks were abandoned, and the majority of the depressions passed north-eastward off the coast of Norway into the Arctic Ocean. The result must have been a great diminution of rainfall over the continent. We shall see later (Chapter XIX) that this period of drought was of extraordinary importance in human history. For during the moist maritime phase central and eastern Europe, and probably also Asia, had become extensively peopled by neolithic nomads of Aryan and Semitic races, while the great river valleys of the south were in the possession of dense agricultural populations in a more advanced state of civilization. As the climate became progressively drier and the pasture diminished, the land was unable to support such a large nomadic population, and there was a great outburst of raiding and conquering expeditions directed southwards and westwards, resulting in a succession of empires in the rich Mesopotamian regions and neighbouring countries, which form the beginnings of our history. The beginnings of history in China also, about 2500 B.C., show that at this time the settled peoples of that country were in trouble with the nomads of the interior.

BIBLIOGRAPHY

Reid, C. "Submerged forests." Cambridge University Press, 1913.

Lewis, F. J. "The history of the Scottish peat-mosses and their relation to the Glacial period." Edinburgh, *Scot. Geogr. Mag.*, 22, 1906, p. 241.

CHAPTER XVI

THE "CLASSICAL" RAINFALL MAXIMUM, 1800 B.C. TO A.D. 500

ABOUT 1800 B.C., or the beginning of the Bronze Age in Britain, the subsiding land finally attained approximately its present level. At the same time the climate of western Europe deteriorated, becoming much more humid and rainy, and there set in a period of intense peat-formation in Ireland, Scotland and northern England, Scandinavia and North Germany, known as the Peat-Bog Period or Upper Turbarian. The peat-beds choked and killed the forests which had developed on the older peat-bogs, and grew up above the stools and fallen trunks, so that we have two layers of peat separated by an old forest. The forest level contains neolithic articles, the peat contains gold collars, bronze swords and pins, and other objects of the Bronze Age. This growth also went on even over high ground, which had not previously been covered by peat, for Professor Henry informs us that on Copped Mountain, near Enniskillen, and at other places in Ireland, Bronze Age cairns and tumuli are found resting on rock and covered by several feet of bog. Peat beds on the Frisian dunes between two layers of blown sand are dated about 100 B.C., and some bogs in northern France were formed during the Roman period. There is also some much-disputed contemporary Latin evidence that at the time of the Roman occupation the climate of Britain was damp and boggy, while Gibbon ("Decline and Fall of the Roman Empire"), referring to the climate of central

Europe at the beginning of the Christian era, points to some evidence that the climate was colder. This is, that the Rhine and the Danube were frequently frozen over, so that the natives crossed them with cavalry and wagons without difficulty, although at the present time this never happens. It is possible that this severe climate is referred to in the Germanic legend of the "Twilight of the Gods," when frost and snow ruled the world for generations. The Norse sagas point to a similar cold period in Scandinavia. This lapse of climate occurred in the Early Iron Age, about 650 to 400 B.C., when there was a rapid deterioration from the high Scandinavian civilization of the Bronze Age. This deterioration of culture was probably the direct result of the increased severity of the climate.

This Pluvial period has been made the subject of special studies by Ellsworth Huntington in several important books and papers; he finds evidence of a distinctly Pluvial period in three regions—the Mediterranean, central and south-western Asia, and an area including the southern United States and northern Mexico. In the first of these, the Mediterranean, Huntington considers that the Græco-Roman civilizations grew up in a period of increased rainfall which lasted from about 500 B.C. to A.D. 200. These states were able to develop in comparative peace because during this time there were no great invasions of nomadic peoples from eastern Europe or central Asia, a fact which points to good rainfall in these comparatively dry regions, so that their inhabitants had no need to emigrate in quest of a living. In the Mediterranean itself the heavier rainfall allowed a solid agricultural basis which produced a sturdy race of peasants who made good soldiers. Owing to the greater cyclonic control of climate and consequent changeable weather, these inhabitants were more vigorous in mind and body, for Huntington's researches have demonstrated that long spells of monotonous weather, either fine or rainy, are

unfavourable for human energy. Finally the heavier rainfall maintained a perennial flow in the rivers, giving plentiful supplies of good drinking water. These conditions broke down earlier in Greece than in Italy, as the latter naturally has a heavier rainfall. Huntington considers that the decline of Greece was largely due to malarial poisoning, the decreasing rainfall causing the river-flow to break down in summer, leaving isolated pools forming a breeding ground for mosquitoes.

After A.D. 200 the climate of Italy also deteriorated. The decrease of rainfall, combined with gradual exhaustion of the soil, made wheat-growing more and more difficult for the small agriculturalist, and the farms came into the hands of large landowners, who worked them by slave labour, and in place of wheat either grew vines or olives or raised flocks and herds. The agricultural population gravitated to Rome and a few other large cities, and had to be fed by imported wheat. The decline was probably aided by the introduction of malaria, as in Greece.

In north Africa and Palestine the question is more debatable. C. Negro, who has investigated the supposed desiccation of Cyrenaica, concludes that there has been no change of climate since Roman times, but a careful study of his evidence suggests that his conclusions are open to criticism. All that he has proved is that there has been no marked *progressive* decrease of rainfall since about A.D. 200; he has ignored the possibility of great fluctuations before and since that date. In north Africa it seems difficult to believe that the great cities of antiquity could have existed under present climatic conditions, but when we turn to Palmyra in the Syrian desert we have practically incontrovertible proof in the great aqueducts, built to carry from the hill-springs to the city large volumes of water which these springs no longer deliver, so that even where they are intact the aqueducts now carry only the merest trickle.

In Persia we find numerous ruins, which point to a much

greater population two thousand or more years ago. This population lived by agriculture, and the remains of their irrigation works are now found in regions where running water never comes. Even the scanty population of to-day can hardly live on the present rainfall of the country, and it is unbelievable that the much greater population indicated by these ruined cities could have existed without a very much greater supply of water. The same condition is indicated by the ruined cities of the great deserts of central Asia. These cities were inhabited by agriculturalists, and the remains of tilled fields, terraces and irrigation works abound in places where the supply of brackish water would now be barely sufficient for drinking purposes for such a large population. Huntington has also made a careful study of the water-level of the Caspian Sea in classical times, and finds that there was a great period of high water extending from unknown antiquity to about A.D. 400.

There is only one region in central Asia where the population appears to have been less in classical times than now, and that is the high basin of Kashmir. Huntington points out that this basin is at present near the upward limit of agriculture, and any fall of temperature and increase of snowfall would drive out the inhabitants. But local legends point to such a period in the remote past, corresponding to the period of increased habitability of the central Asian deserts; at its close there were extensive migrations from Turkestan into Kashmir.

Passing to America, we come to interesting evidence of a very different class—I refer to the "big trees" (*Sequoia*) of California. Since these trees live in a semi-arid climate, the amount of rainfall is the chief factor in their growth, which finds an expression in the breadth of the annual rings measured on the stump of the tree when it is cut down. The method of utilizing the data was due to A. E. Douglass. A careful comparison was first made between the measurements of rings and the

rainfall measured at neighbouring stations, and a formula was developed by which the rainfall of each year could be reconstructed from the tree-growth with a high degree of accuracy. In extrapolating to find the rainfall for earlier years before rainfall measurements began, various corrections had to be applied, for instance trees grow more rapidly when young than when they are old, while trees which are likely to live to a great age grow more slowly at first than trees which die younger. These methods were applied to nearly two thousand "big trees," some of which were found to be four thousand years old, but it is pointed out that the corrections eliminate any progressive variation of climate which may have occurred, so that the results show only "cycles" of greater or lesser length. Summing up, Huntington says: "Judging from what we have seen of the rainfall of to-day and its relation to the growth of the Sequoias, high portions of their curve (of growth) seem to indicate periods when the winters were longer than now, when storms began earlier in the fall and lasted later into the spring, and when mid-winter was characterized by the great development of a cold continental high-pressure area, which pushed the storms of the prevailing zone of westerly winds far down into sub-tropical regions and thus caused sub-tropical conditions to invade what is now the zone of equatorial rains." Neglecting later favourable periods, which are relatively short and unimportant, it is found that these conditions prevailed very markedly between 1200 B.C. and A.D. 200, with maxima about 1150 B.C., 700 B.C., and from 450 B.C. to 250 B.C.

Thus over the greater part of the temperate regions of the northern hemisphere we have evidence of an important rainy period between the extreme limits of 1800 B.C. and A.D. 400 or 500. This period was best developed from 1200 B.C. to A.D. 200, and reached its maximum about 400 B.C. It constitutes a remarkable wave of climatic variation, which is hitherto without

adequate explanation. A somewhat similar, though less intense, wave which occurred about A.D. 1200–1300, and which is described in the following chapter, was associated by Wolf to a great outburst of sunspots which took place about A.D. 1200. It is well known that sunspots are an index of solar activity, the sun's radiation being greater at times of spot maximum than at times of spot minimum. Greater solar radiation increases the evaporation over the oceans, so that the air becomes more humid. This moist air is carried by atmospheric currents over the land, where the moisture is condensed into clouds and greatly increases the rainfall. At the same time the cloud canopy shuts off some of the direct heat of the sun, and we have the curious paradox that at times of sunspot maximum, or greatest solar radiation, the temperature of the earth's surface is lowest.

The connexion outlined above is, however, extremely problematical for temperate regions. Since the absolute sunspot maximum at A.D. 1200 is also very doubtful, it will be realized that the evidence for the sunspot hypothesis of the mediæval rainfall maximum is extremely slender. Furthermore, since we know nothing whatever about the solar activity during the classical rainfall maximum, we are still less in a position to extend the sunspot hypothesis to that period also.

The interesting theory recently put forward by O. Pettersson, already alluded to, provides a plausible alternative explanation of the severe stormy climate of the Peat-bog period, which reached a maximum near 400 B.C. Without going into details this theory is that the strength of the tides depends on the relative positions of the sun and moon, and the tides are greatest when these act in conjunction, and also when they are nearest to the earth. This fluctuation of strength passes through various cyclic variations with periods of nine years, about ninety years and about 1800 years, though the lengths of the periods are not constant. The latter cycle is most important to our purposes; according to

Pettersson's calculations the fluctuations of the "tide-generating force" were as follow:

Maxima	3500 B.C.	2100 B.C.	350 B.C.	A.D. 1434
Minima	2800 B.C.	1200 B.C.	A.D. 530.	

Increased range of the tides means increased circulation in the waters of the oceans, especially an increased interchange between the warm North Atlantic and the cold Arctic waters. It also means than an unusual amount of ice is brought down from high into low latitudes. Wide local variations of temperature of the surface waters of the oceans cause increased cyclonic activity, and hence we may expect a generally increased storminess at times of maximum "tide-generating force," and the reverse at times of minimum.

For the last maximum (A.D. 1434) Pettersson is able to adduce a good deal of historical evidence of increased storminess in north-west Europe and bad ice-conditions near Iceland and Greenland, while Huntington has found an increase of rainfall shown by the big trees of California. The next preceding maximum, that of 360 B.C., marks the culminating point of the Peat-bog phase. The Norse sagas and the Germanic myths point to a severe climate about 650 B.C., which destroyed an early civilization. This was the "Twilight of the Gods," when frost and snow ruled the world for generations. The period was the Early Iron Age, when civilization deteriorated greatly in north-west Europe.

Of the maximum of 2100 B.C. there is no trace. It is possible that the great Atlantic submergence of the Maritime phase is connected with the tidal maximum of 3500 B.C., but the phenomena were on a scale so much greater than those of the more recent maxima that this can hardly have been the sole cause.

The minima should have been characterized by periods of relatively quiet stable climate with little ice near Iceland and Greenland. That the last minimum,

in A.D. 530, was such a period there is considerable evidence in the high level reached by civilization at that period in Scandinavia and by the revival in Ireland. Again, about 1200 B.C., in the early part of the Peat-bog phase, there is evidence of considerable traffic by sea between Scandinavia and Ireland. The Irish Museum has lately discovered a hoard of gold objects dated about 1000 B.C., in which the designs show a Scandinavian origin. The minimum of 2800 B.C., which occurred in the Forest phase, may have contributed to the dry climate of that period, but otherwise has left no trace.

Although at first sight the effect which Pettersson sets out to explain seems out of all proportion to the smallness of his cause, the coincidences after 2000 B.C. are extremely interesting, and suggest that after the land and sea distribution reached its present form the astronomical cause adduced by Pettersson was possibly effective, but before that date the astronomical cause, if it existed, was masked by the much greater climatic variations due to changes in the land and sea distribution.

The opinion has frequently been expressed that the "Classical" and "Mediæval" rainfall maxima were phenomena similar to the Glacial period, but less intensive. This view is often carried to its logical conclusion, that the thirty-five-year cycle, the eleven-year, and still smaller cycles of climate, are also part of the same series, and that the Glacial period and, let us say, the three-year periodicity of rainfall are therefore due to variations of the same agent, in this case the sun. This logical extension of the theory is, however, completely untenable. The eleven-year periodicity is admittedly connected with variations in the solar activity, but there are other cycles which are completely independent of such variations, such as, for instance, the annual variation undergone by all meteorological elements, which depends entirely on the inclination of the earth's axis. There is a well-marked 4.8 year period in the amount of ice off Iceland, the half-cycle of which is

exactly equal to the distance travelled by the water taking part in the North Atlantic circulation, divided by the velocity with which it travels. There is, therefore, no *a priori* reason for assuming that the cause of the Glacial period was identical with the cause of the Classical and Mediæval rainfall maxima. Further, in the latter case, the chief phenomenon was the increase of rainfall; the decrease of temperature was merely incidental, but in the Glacial period the outstanding feature was a great lowering of temperature in the polar and temperate regions, and in this case it was the increase of rainfall which was incidental.

BIBLIOGRAPHY

Lewis, F. J. "The history of the Scottish peat-mosses and their relation to the Glacial period." Edinburgh, *Scot. Geogr. Mag.*, 22, 1916, p. 241.

Brooks, C. E. P. "The correlation of the Quaternary deposits of Great Britain with those of the Continent of Europe." *Ann. Rep. Smithsonian Inst.*, 1917, p. 277.

Huntington, Ellsworth. "The pulse of Asia." Boston and New York, 1907.

———. "The climatic factor as illustrated in arid America." Washington, *Carnegie Institution*, 1914.

———. "World power and evolution." New Haven, 1919, pp. 186–207.

Pettersson, O. "Climatic variations in historic and prehistoric time." *Svenska Hydrogr.-Biol. Komm. Skrifter*, Heft 5.

CHAPTER XVII

THE CLIMATIC FLUCTUATIONS SINCE A.D. 500

THE question of climatic changes during the historic period has been the subject of much discussion, and several great meteorologists and geographers have endeavoured to prove that at least since about 500 B.C. there has been no appreciable variation. It is admitted that there have been shiftings of the centres of population and civilization, first from Egypt and Mesopotamia to the Mediterranean regions, and later to northern and western Europe, but these have been attributed chiefly to political causes, and especially to the rise of Islam and the rule of the "accursed Turk." Recently, however, there has arisen a class of evidence which cannot be explained away on political grounds, and which appears to have decided the battle in favour of the supporters of change; I refer to the evidence of the trees, explained in the preceding chapter. The conclusions derived from the big trees of California have fallen admirably into line with archæological work in central America, in central Asia and other regions, and have shown that the larger variations even of comparatively recent times have been very extensive, if not world-wide, in their development.

Let us consider first the evidence of the trees. These indicate that after the moist period ending about A.D. 400, described in the preceding chapter, the rainfall was generally light until about A.D. 1000, when it showed a sharp rise, probably to the level attained in A.D. 1. (The correction for age renders an exact comparison

between periods a thousand years apart difficult.) This period of abundant rainfall lasted some fifty years, followed by a gradual decline to a brief minimum, shortly before A.D. 1200. About 1300 occurred another rapid rise, reaching a maximum before 1350; the period of heavy rain continued a short while after 1400, when a decline set in, reaching a minimum at 1500, after which the rainfall recovered somewhat, and subsequently maintained approximately its present level, with a slight maximum about 1600 to 1645.

In the desert of Arizona, in regions at present too dry for agriculture, there are abundant ruins, which are attributed by Huntington to three periods:

(*a*) Pueblo ruins, dating back to just before the coming of the Spaniards (i.e. about A.D. 1600), and indicating merely an increase of population at the present centres.

(*b*) Ruins of an older civilization, termed by Huntington the Pajaritan, during which numerous inhabitants lived in places where at present no crops can be raised. "These people, as appears from their pottery, their skulls and their methods of agriculture, belong to a different civilization from that of the modern Pueblas who inhabited Gran Quivera at the time of the coming of the Spaniards. They had evidently disappeared long before that date, as is evident from the present ruins of their villages, and from the absence of any hint of their existence in the early annals of the country" (*Geogr. Journal*, 40, 1912, p. 396).

The largest ruins of this type invariably lie near the main lines of drainage. They consist of villages with houses of several storeys. But digging down beneath these ruins we find (*c*) traces of an older occupation, and ruins of a primitive type are also found on the plateaus remote from any except small valleys. "They are usually small, and are greatly ruined, and seem to belong to a time long anterior to the main large ruins." Huntington terms this type the Hohokam; unfortunately

this and the Pajaritan occupations cannot be accurately dated, but it is reasonable to connect them with the rainfall maxima shown by the trees, about the time of Christ, and in A.D. 1000 to A.D. 1300.

A similar succession has been found in the neighbourhood of Mexico City. The earliest trace of occupation is a crude "mountain pottery," in ordinary river sand and gravel. These deposits are succeeded by finer sand with better pottery known as the "San Juan" type, above which comes a culture layer with the remains of houses. This is covered by a bed of "tepetate," a white calcareous deposit frequently found in dry regions where much water evaporates. The gravels suggest the occasional heavy rains of arid countries. The San Juan pottery extends throughout the "tepetate," which probably corresponds to the dry period of A.D. 400–1000 in California.

Historical records in Mexico date back to the coming of the Aztecs in A.D. 1325. They show that in 1325 and again in 1446 the level of the lake of Mexico was high, but towards the end of the fifteenth century the water was much lower. In 1520 it was high again; in 1600 it was low, but high from 1629 to 1634. From 1675 to 1755 was a long dry period. On the whole the climate from 300 to 600 years ago seems to have been moister than that of to-day.

Still further south in the Peninsula of Yucatan recent explorations have yielded results of extreme interest. Yucatan lies within the tropical rain-belt, and is covered by almost impenetrable forests. The climate is enervating and unhealthy, and the present inhabitants are greatly lacking in vigour. In the forest, however, have been found the ruins of ninety-two towns, some of them of great size, and all remarkable for the beauty as well as the solidity of their architecture.

These ruins belong to the great Mayan civilization. Mayan history has been briefly summarized by Huntington as follows: "First we have a long period of active

development, during which the calendar was evolved and the arts of architecture and sculpture were gradually developed. . . . This time of marked growth must have preceded the Christian era. Then comes . . . the building of the great cities of Copan, Quirigua, Tikal and others. These first great cities were in the southern part of the Maya area, on the borders of Honduras or in eastern Guatemala. They lasted perhaps three or four centuries; then quickly declined. So far as we have any evidence, civilization never revived in this southern area, for the structures of the great period have not been rebuilt by later inhabitants. Towards the end of the period of greatness the centre of Mayan culture moved northward. . . . The great period, according to Bowditch, lasted from 100 B.C. to A.D. 350 . . then came a time of very low civilization, lasting for centuries. . . . A revival ensued about A.D. 900 or A.D. 1000, and architecture once more reached a high pitch, but . . . only in northern Yucatan; all the rest of the country seems to have remained in darkness. Moreover, this mediæval revival was relatively shortlived. Since that time the condition of the Mayas has fluctuated more or less, but on the whole there has been a decline."

Now at the present day the densest and most progressive population in Yucatan is found in the driest part of the country, where the forest gives place to jungle. If the line of separation between jungle and forest were moved southward 300 miles, the former would include all the districts where ruins are now found. We see from the above summary that the prosperous periods of Mayan history were just those periods which in California were moist; in Yucatan they must have been dry. Huntington's explanation is the theory of the "shifting of climatic belts"; during the rainy period in California the temperate storm-tracks were shifted further southward. At the same time the sub-tropical high-pressure belt, which at present lies over the West Indies, was also shifted southwards and

this brought a dry cool winter to Yucatan, with an increased contrast of seasons, and consequently a more invigorating climate.

In Asia, Huntington and other explorers have found similar traces of past variations of climate, a fascinating account of which is given in "The Pulse of Asia." Space will not permit of a summary in detail, but the following general conclusions may be quoted :[1]

"If we omit the Volga and the European portions of the Caspian drainage area, the limits (of the six basins considered) lie over sixteen hundred miles apart from north to south and over three thousand from east to west. All this great area seems to have been subject to the same great waves of climatic change.

"In the ancient days when the Oxus River entered the Scythian Gulf of the expanded Caspian Sea, and Lake Gyoljuk discharged permanently to the Tigris, the lake of Seyistan had not been converted into dry land by the giants. Kashmir was so cold and snowy that agriculture was impossible. . . . In the Lop basin the rivers were full of water ; Lop-Nor was the "Great Salt Lake" ; the desert was comparatively small and the zone of vegetation extensive ; and on all sides there was a density of population and a degree of prosperity far beyond those of to-day. And in the Turfan basin the same was probably true.

"A great change took place throughout the six basins during the early centuries of the Christian era. The lakes of Gyoljuk, Seyistan, the Caspian, Lop-Nor and presumably Turfan were greatly reduced in size. In the case of the first three, parts of the old lake-beds were used as sites for villages. Except in Kashmir, the change of climate appears to have brought disaster. . . .

"Again there came a change (about A.D. 700). The process of desiccation gave place to a slight but important tendency toward increased rainfall and lower tempera-

[1] "The pulse of Asia," p. 356. See also a new work by E. Huntington, entitled : "Climatic changes."

ture. Kashmir became colder and more snowy, and hence more isolated; the rivers of Lop and Turfan gained greater volume; and the lakes of Lop, the Caspian and Turfan expanded once more. The habitability of the arid regions began to increase; migrations came to an end; and central Asia was prosperous for a time. Finally (about 1350) a latest and slightest change took place in the other direction, and we seem to-day to be in the midst of an epoch of comparative equilibrium, with no marked tendency towards climatic change in either direction." There was, however, a period of comparatively high water in the Caspian in the early part of the seventeenth century.

In Europe the evidence for climatic changes during historical times is more difficult to follow, since variations of rainfall leave fewer traces in a moist than in an arid or semi-arid country. A certain amount of material is given by Brückner in his "Klimaschwankungen." He finds that there was a great advance of the Alpine glaciers from 1595 to 1610, while two Italian lakes without outlet, the Lago di Fucina and Lake Trasimeno, attained a high level about the same time. Other evidence for western Europe is derived from the date of the wine-harvest and from the records of severe winters. Like the growth-curves of the big trees, they need a secular correction to alter the general slope of the curve, especially in the case of severe winters, but the larger irregularities probably correspond to real variations of climate. I have added in column 4 the numbers of winters with sea-ice on some part of the Danish coast, as tabulated from the records compiled by Captain C. I. H. Speerschneider. The results are in general agreement with column 3, particularly as showing that the period 1401–50 was relatively mild; but the first half of the seventeenth century is less instead of greater than its two neighbours in this column.

The figures for the wine-harvest refer to the average for the period 1816–80; — indicates that the harvest

was so many days earlier than normal, corresponding to a high summer temperature (May to August). The table shows that cold winters were especially numerous in the first half of the twelfth century and again in the thirteenth. The end of the fifteenth century was marked by hot summers and mild winters, or a warmer climate; the beginning of the seventeenth

1. Period, 50 years about.	2. Date of Wine Harvest.	3. No. of Severe Winters.	4. Winters with Ice on Danish coast.	5. Remarks.
825		4		
875		7		
925		5		
975		6		
1025		6		
1075		10		
1125		15		Cold winters
1175		10		
1225		13		
1275		13		Cold winters
1325		13	7	
1375		11	4	
1425	+5	13	7	
1475	+1	7	2	Warm
1525	+2·9	10	5	
1575	+2·2	14	14	
1625	+4·1	17	11	Cold
1675	+2·7	15	14	
1725	+0·1	10	5	
1775	−0·2	—	22	
1825	−0·9	—	21	

century by cold (presumably snowy) winters and cool summers. Thus the periods of increased rainfall in the arid regions of Asia and America were marked by a colder climate in the rainy regions of western Europe.

The date of the break up of the River Dwina at Mitau was recorded intermittently from 1530 to 1709, and regularly since that date, and the figures have been

discussed by Rykatchef. Recasting them in our unit of fifty years we find the mean dates to be:

1551–1600	1601–50	1651–1700	1701–50	1751–1800	1801–50
March 29	March 30	March 5	March 26	March 26	March 28

This again points to a cold period about the beginning of the seventeenth century.

The climate of Iceland and Greenland in the Middle Ages has been the subject of much controversy, the view that there were extensive changes during that period being warmly upheld by one party and as warmly combated by the other party. The case for climatic change has been well set out by O. Pettersson[1]. The Roman authors (Pliny, Solinus, etc.) wrote that there was a frozen sea about Thule (Iceland), but a party of monks who visited the island about A.D. 795 during the months of February to August, in which the ice is normally most abundant in Icelandic waters, found the coast free, though they met with a frozen sea a day's journey to the northward. In the ninth century the Norsemen visited Iceland regularly, and at times sailed round it, apparently without interference from ice. The early settlers practised agriculture with some success. In the thirteenth century, however, the reports of ice off Iceland became frequent—apparently the conditions were worse than those of the present day, and much more so than in the eighth and ninth centuries. According to Rabot, it appears from ancient records that considerable areas cultivated in the tenth century are now covered with ice. The first spread of the glaciers took place in the first half of the fourteenth century. In the fifteenth and sixteenth centuries the climate of Iceland ameliorated somewhat, but in the seventeenth there was a readvance, which destroyed several farms about 1640 or 1650. Since then there has been a slight retreat.

[1] "Climatic variations in historic and prehistoric time."

The ice conditions of Greenland are closely related to those of Iceland, and the records of the Norse colonization of Greenland bear out the conclusions drawn from the latter island. Up to the close of the twelfth century ice is hardly ever mentioned in the accounts of voyages, though it is now a great hindrance. Eric, the pioneer explorer of West Greenland, spent three successive winters on the islands in Juliaanehaab Bay (latitude 60° 45′ N.), and explored the country during the summer; "this cannot be explained otherwise than by assuming that the Polar ice did not reach Cape Farewell and the west coast of Greenland in those days." In the thirteenth century ice is first specifically mentioned as a danger to navigation, and at the end of the fourteenth century the old Norse sailing route was on account of ice definitely abandoned in favour of one further south. Shortly afterwards the Norse colonies were wiped out by a southward migration of the Eskimos. Even in Norway itself the fourteenth century was a time of dearth, short harvests and political troubles, when corn had to be imported from Germany instead of being exported to Iceland as in former years.

It should be noted that Pettersson's conclusions are considered invalid by H. H. Hildebrandsson[1] on the ground of the incompleteness of the records.

For the southern hemisphere our records are naturally much rarer and of less antiquity than for the northern hemisphere, and until the tree-rings are investigated we cannot carry our study back beyond the sixteenth century. From some researches into the municipal archives of Santiago de Chile, latitude 33½° S., published by B. V. Mackenna in 1877, we can infer, however, that the general course of variation since 1520 was similar to that of corresponding regions in North America. Santiago lies in a semi-arid region where a temporary shortage of water is severely felt, the average annual rainfall being only 364 mm. (14.3 inches). The early

[1] Sur le prétendu changement du climat européen en temps historique."

travellers, however, make no specific mention of drought, and in 1540 Pedro de Valdivia crossed the desert of Atacama with a column of troops and cattle without inconvenience—a feat which would be difficult nowadays. In 1544 there were heavy rains and great floods in June. The next record is for the year 1609, recording another heavy flood on the Mapocho, which was repeated nine years later in 1618. The first recorded drought occurred in the years 1637 to 1640; there was another flood in 1647, after which came a series of severe droughts interrupted by occasional floods, which lasted until the close of the eighteenth century. The first half of the nineteenth century was again comparatively rainy. The records thus indicate a wet period centred about 1600, followed by a dry period during the eighteenth century, exactly parallel to the records from the United States and Europe.

BIBLIOGRAPHY

Huntington, E. "The climatic factor as illustrated in arid America Washington, Carnegie Institution, 1914.

———. "The fluctuating climate of North America." *Geogr. J.*, 40, 1912, pp. 264, 392.

——— "The pulse of Asia." Boston and New York, 1907.

———. "World power and evolution." New Haven, 1919.

Pettersson, O. "Climatic fluctuations in historic and prehistoric time." *Svenska Hydrogr.—Biol. Komm. Skrifter*, H. 5.

Rabot, Ch. "Essai de chronologie des variations glaciaires." *Bull. geogr. historique et descriptive*, No. 2, 1902.

Brückner, E. "Klimaschwankungen seit 1700" . . . Vienna, 1890.

Hildebrandsson, H. H. "Sur le prétendu changement du climat européen en temps historique." Upsala, *Nova Actae Regiae Soc. Sci.* (4), Vol. 4, No. 5, 1915.

Brooks, C. E. P. "An historical notice of the variations of climate in Chile." Washington, *Dept. Agric., U.S. Weather Bureau, Monthly Weather Rev.* 47, 1919, p. 637.

CHAPTER XVIII

CLIMATIC FLUCTUATIONS AND THE EVOLUTION OF MAN

THE origin of man from an ape-like ancestor[1] is generally admitted, but owing to the incompleteness of the palæontological record we are still in ignorance as to the circumstances, while the place is generally put vaguely as somewhere in Asia, and the time as the late Tertiary (Prof. Elliot Smith places it near the Siwalik hills in the Miocene). For this early period we are reduced to speculation, in which we may reasonably utilize the facts which we have gained about climatic variation.

The chief problem to be explained is why man's arboreal ancestor left the safe shelter and easy food supply of his primæval forest and ventured forth into the plains. An article by Professor J. Barrell,[2] of Yale University, gives a plausible account of the change, putting it down to necessity, and not to choice. His theory is that the human ancestor lived in the forests spread over Asia, then a vast well-watered plain, during the middle Tertiary period. Then the gradual uplifting of the Himalayas and other mountain ranges caused a decrease in the rainfall of central Asia, so that ultimately the forests were unable to thrive, and gradually gave place to steppe conditions. The change was slow enough to give the less specialized inhabitants of the

[1] Or lemur-like ancestor. There is evidence to show that man's ancestor was a nocturnal animal, whose food-supply was governed by the phases of the moon.

[2] "Scientific monthly," New York, 4, 1917, pp. 16–26.

forest time to change their habits and evolve into forms suitable to a terrestrial life, and the chief of the animals which took advantage of this period of grace was the pre-human. Forced to live on the ground, with a diminishing food supply, only the most progressive individuals were able to survive, and evolution was rapid. The changing type was saved from being submerged in the great mass of the original type in the forests which continued to exist further south by the impassable wall of mountains. Major Cherry[1] considers that there is sufficient evidence to prove that a portion of this evolution took place on the seashore, an environment which would have been much more favourable to a small ape-like animal than the open steppe would have been. It is quite likely that the earliest migrations, such as that which carried *Pithecanthropus* to Java, took place along the shore. But after a time, when increasing brain-power and the use of primitive stone implements enabled man to take the offensive against the larger animals, the centre of activity changed to the steppes. A familiar view of the early development of man was advocated by W. D. Mathew,[2] who writes: "In view of the data obtainable from historical record, from tradition, from the present geographical distribution of higher and lower races of men, from the physical and physiological adaptation of all and especially of the higher races, it seems fair to conclude that the centre of dispersal of mankind in prehistoric times was central Asia, north of the great Himalayan ranges, and that when by progressive aridity that region became desert it was transferred to the regions bordering it to the east, south and west. We may further assume that the environment in which man primarily evolved was not a moist tropical climate, but a temperate and more or less arid one, progressively cold and dry during the course of his evolution. In this region and under these

[1] "Science progress," 15, 1920, p. 74.
[2] "Climate and evolution."

conditions, the race first attained a dominance which enabled it to spread out in successive waves of migration to the most remote parts of the earth."

We do not know anything of the migrations of the Eolithic and earlier Palæolithic races, except that they spread rapidly over a considerable portion of the earth. Both migration and evolution, especially mental evolution, must have been accelerated by the great changes of climate which were taking place. In the Mindel-Riss interglacial period we know of two types, the Piltdown man (*Eoanthropus dawsoni*) and the Heidelberg man (*Homo heidelbergensis*), the latter a true man, though probably not on the direct line of evolution of *Homo sapiens*. The stress of the succeeding second Glacial period was too great for *Eoanthropus*, which appears to have died out, but *Homo*, probably an Asiatic or African type similar to *H. Heidelbergensis*, survived. The next form, associated with Mousterian implements, is Neanderthal man (*H. neanderthalensis*), who closely resembled modern man, and all the remains of races which lived subsequently to the last glaciation are those of modern man (*H. sapiens*), including the magnificent Cro-Magnards and the negroid Grimaldi race. Thus each glaciation has been marked by a step upwards in the scale of humanity; does this mean that the coming of the super-man is contingent on another glacial epoch?

BIBLIOGRAPHY

Barrell, J. "Probable relations of climatic change to the origin of the Tertiary Ape-man." *Scientific Monthly*, New York, 4, 1917, p. 16.

Mathew, W. D. "Climate and evolution." *Annals New York Acad. Sci.*, 24, 1915, p. 212.

London, British Museum. "A guide to the fossil remains of man . . ." London, 1918.

CHAPTER XIX

CLIMATE AND HISTORY

It is a remarkable fact in human history that civilization began in regions which are at present inhabited chiefly by backward races, and the centres of progress have shifted from one country to another with the passage of time. Many accidental factors—position on trade-routes, possession of special mineral advantages, and so on, have undoubtedly played a part in this, but it will not be difficult to show that climatic fluctuations have also had their share.

A brilliant study of Ellsworth Huntington[1] has shown that there are certain optimum conditions of climate which are most suitable for efficient work. These conditions, which were determined by an analysis of the output of work in American factories, were then found to be just those which prevail in the most progressive regions of the globe, which are located in the temperate storm-belts, and it is shown in certain instances that fluctuations in the position of this storm-belt coincided with fluctuations in the centres of civilization. A few additional examples of this may be given.

The beginnings of civilization may reasonably be placed with the transition from the Palæolithic to the Neolithic type, a transition which involved much more than just the polishing of stone weapons. It involved also the beginnings of agriculture, crude pottery, and

[1] "Civilization and climate."

later, the domestication of animals. One of the earliest Neolithic cities known is probably that of Anau, near Askabad in Transcaspia, excavated by Pumpelly in 1904. From the thickness of the accumulated debris the date of first settlement is placed at or before 8000 B.C., i.e. 10,000 years ago, or during the period which in Europe is assigned to the concluding stages of the Wurm glaciation. Pumpelly's time-estimates are based on careful comparison with accumulations in Merv and other cities. At present the mean annual rainfall in that part of Turkestan is below ten inches a year, and the country is practically desert, and is entirely unfitted for agriculture. But with the remains of the ice-sheet still over Scandinavia and depressions following a more southerly course along the Mediterranean basin and into southern Asia, the rainfall was considerably heavier, and the climate in general was more suited to a progressive race. At the outset we find this Neolithic race living in rectangular houses built of uniform sun-dried bricks; they were skilful potters, cultivating cereals, but at first without domestic animals.

The beginning of Neolithic civilization in Crete is placed by Evans at about 12000 B.C., while on the basis of excavations by de Morgan at Susa in Persia, Montelius places the origin of Neolithic culture in this part of Asia as early as about 18000 B.C. At Susa the deposits are 130 feet thick, and of these the upper 40 feet cover a period of 6000 years.

Thus we see that what may be considered as the great step from savagery to civilization took place while the present centres of progress in Europe and America were still in the Ice Age. At this time the climate of southern Asia must have resembled the present climate of north-west Europe in heavier rainfall and the day-to-day fluctuations of weather—in fact, the districts where civilization began probably had at that time the most stimulating climate in the northern hemisphere.

With the vanishing of the ice-sheets and the setting

in of the mild climate of the Maritime phase the Neolithic culture spread rapidly to Europe, and by 2000 B.C. even the Baltic regions were well inhabited, and it is probable that the Aryan race was developing in the Russian steppes. About this time Anau was abandoned owing to increasing aridity.

With the coming of the Bronze Age in western Europe, about 1800 B.C., however, the climate again became colder and rainier, corresponding to the Peat-bog phase or "Classical" rainfall maximum, the deterioration culminating in the Early Iron Age. This period was marked by a great southward spread of the Aryan peoples, and ushered in the Heroic Age of Greece. The races of the Mediterranean, as we have seen, continued to thrive throughout this rainy period, and their power did not diminish until its close, about A.D. 400. This downfall was accelerated if not caused by the pressure of nomad peoples driven out of Asia by the increasing drought. These Asiatic migrations included the great marches of the Tartar hordes and, aided by religious enthusiasm, the conquests of the Moslems.

The early Middle Ages, after the downfall of Rome, appear to have been characterized by a dry warm climate. This was the age of the Vikings, when the Norse races rose to dominance in western Europe, finally invading and occupying large areas of France and Britain, and even extending their power to Sicily. With the increasing cold and wet of the "Mediæval" rainfall maximum came a final burst of Norse migration, which left the homeland poor and scantily populated, and the centre of activity and progress lay once again with the Mediterranean peoples, and especially with Italy and Spain. The Tartar invasions ceased, and against the increasing power of Europe the Moslem wave broke and receded. At the close of this rainy period political dominance again moved north. From that time the fluctuations of climate have been of minor importance, and corres-

pondingly there have been no great shiftings of political power from latitude to latitude.

BIBLIOGRAPHY.

Tyler, J. M. "The New Stone Age in Northern Europe." London 1921.
Huntington, Ellsworth, "World Power and Evolution." New Haven, 1919.
Haddon, A. C., "The wanderings of peoples." Cambridge University Press, 1919.

APPENDIX

THE FACTORS OF TEMPERATURE

To calculate the probable temperature of January or July at any point, the following procedure should be adopted :

Draw a circle round the point of angular radius ten degrees (i.e. set the compass to cover ten degrees of latitude) and divide this into two halves by a line passing from north to south through the centre. By means of squared tracing paper, or otherwise, measure : (*a*) the amount of ice in the whole circle ; (*b*) the amount of land in the western half ; (*c*) the amount of land in the eastern half. (*a*) is expressed as a percentage of the area of the whole circle ; (*b*) and (*c*) as percentages of the area of a semicircle.

The term " ice " includes ice-sheets such as that of Greenland or Antarctica, and also frozen sea or sea closely covered by pack-ice ; the latter figure may vary in different months.

The temperature in January or July is then calculated from the following formula :

Temperature = basal temperature + ice coeff. × per cent. of ice + land west coeff. × per cent of land to west + land east coeff. × per cent of land to east.

The basal temperatures and the appropriate coefficients are given in the following table.

In calculating the effect of a given slight change of land and sea distribution, it is not necessary to employ the basal temperature. Instead the equation can be treated as a differential, and the change of temperature

due to the change of land and ice calculated from the figures in columns 3 to 5. The figures are given in degrees absolute, 273°0=32° F. To convert differences to Fahrenheit, multiply by 1°8.

In the case of the calculation of the effect of comparatively slight and irregular changes in land and sea

Latitude.	Basal Temp. (Water Zone).	Ice Coeff.	Land, West Coeff.	Land, East Coeff.
Jan.	a.			
70 N.	298·8	− 0·49	− 0·43	− 0·20
60	277·4	− 0·07	− 0·31	− 0·01
50	276·8	− 0·09	− 0·29	0·09
40	282·5	—	− 0·17	0·04
30	289·6	—	− 0·08	0·03
20	294·2	—	− 0·01	− 0·01
10	298·6	—	− 0·01	0·03
0	299·3	—	0·01	0·00
10 S.	298·2	—	0·04	− 0·01
20	296·2	—	0·07	0·00
30	293·5	—	0·06	0·03
40	289·3	—	0·09	− 0·03
July.				
70 N.	279·3	− 0·16	0·02	0·02
60	280·7	—	− 0·01	0·11
50	285·8	—	0·04	0·06
40	291·1	—	0·05	0·07
30	296·8	—	0·08	− 0·01
20	297·6	—	0·07	0·02
10	298·8	—	0·03	− 0·01
0	298·6	—	0·02	− 0·01
10 S.	296·9	—	0·04	− 0·03
20	293·1	—	0·02	− 0·02
30	288·2	—	− 0·01	− 0·01
40	284·0	—	0·00	− 0·03

distribution in a limited area, such as those of the *Littorina* Sea referred to on p. 128, it may be found that a ten-degree circle is too wide an area to employ, the changes from land to sea at one point being nullified by changes from sea to land at another more distant point. In such a case a smaller unit such as a circle of five degrees radius can be employed. As a rough

approximation it may be said that the effect of the conversion of a square mile of land into sea, or *vice versa*, on the temperature of a neighbouring point is inversely proportional to its distance. Since the area of a five-degree circle is one-quarter that of a ten-degree circle, while the average distance of the land composing it is one-half, we have to divide our regression coefficients by two in order to fit the new data.

This method was applied to obtain the probable temperature distribution on the shores of the *Littorina* Sea at its maximum extension, and gave results which agreed remarkably well with those calculated by geologists from the animal and plant life of the time.

See London *Q. J. R. Meteor. Soc.*, 43, 1917, pp. 169–171.

INDEX

Printed in Great Britain by Jarrold & Sons, Ltd., Norwich.